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WIND-TUNNEL INVESTIGATION OF SEVERAL LARGE-SCALE ALL-FLEXIBLE PARAWINGS

by

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and

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Ames Research Center

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16. Abstract Parawings with 15- to 24-foot keel lengths were tested to determine their longitudinal force characteristics. The configurations tested were constructed by different techniques (glued, sewn, and sewn with reinforcing tapes), and one had multiple radial canopy slots. They were tested over a range of forward velocities. The differences in their aerodynamic characteristics were small (approximately 0.25 in lift-drag ratio). At low resultant forces the lift-drag ratio (L/D) of the configuration with multiple radial canopy slots was lower by 0.5 than that of the other single keel configurations. The results of the tests agreed well with small-scale results (5-ft keel length). Increasing the free-stream velocity from 29 to 58 feet per second reduced the L/D from a small decrement to approximately 0.5 for all the parawings tested except the 15-foot single keel which had no change in L/D with velocity.					
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NOTATION

C_D	drag coefficient, $\frac{\text{drag}}{qS}$
C_L	lift coefficient, $\frac{\text{lift}}{qS}$
C_R	resultant force coefficient, $\sqrt{C_L^2 + C_D^2}$
l_K	length of keel from theoretical apex to trailing edge at the plane of symmetry (fig. 2(a)), ft
$\frac{l}{l_K}$	dimensionless length of suspension lines measured from keel or wing leading edge to the main riser test apparatus attachment
$\frac{l_K}{l_K}$	dimensionless length of keel trailing-edge suspension line (fig. 1(a)), ft
$\frac{l_T}{l_K}$	dimensionless length of wing-tip suspension line (fig. 1(a)), ft
$\frac{L}{D}$	lift-to-drag ratio, $\frac{C_L}{C_D}$
q	free-stream dynamic pressure, psf
S	flat pattern (planform) area of canopy, ft ²
$\frac{x_K}{l_K}$	dimensionless distance to canopy line attachment point from theoretical apex along wing keel (figs. 2(a) and 6(a))
$\frac{x_{LE}}{l_K}$	dimensionless distance to suspension line attachment point from theoretical apex along wing leading edge (figs. 2(a) and 6(a))

WIND-TUNNEL INVESTIGATION OF SEVERAL LARGE-SCALE

ALL-FLEXIBLE PARAWINGS

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SUMMARY

Parawings with 15- to 24-foot keel lengths were tested to determine their longitudinal force characteristics. The configurations tested were constructed by different techniques (glued, sewn, and sewn with reinforcing tapes), and one had multiple radial canopy slots. They were tested over a range of forward velocities. The differences in their aerodynamic characteristics were small (approximately 0.25 in lift-drag ratio). At low resultant forces the lift-drag ratio (L/D) of the configuration with multiple radial canopy slots was lower by 0.5 than that of the other single keel configurations. The results of the tests agreed well with small-scale results (5-ft keel length). Increasing the free-stream velocity from 29 to 58 feet per second reduced the L/D from a small decrement to approximately 0.5 for all the parawings tested except the 15-foot single keel which had no change in L/D with velocity.

INTRODUCTION

Different types of gliding parachutes are being developed for spacecraft recovery and cargo delivery. One of these is the all-flexible parawing, which has been investigated mainly in small-scale studies (refs. 1 and 2). Since more large-scale aerodynamic data are needed to supplement the few large-scale investigations (e.g., refs. 3 and 4), a series of all-flexible parawings with 15- to 24-foot keel lengths was tested in the Ames 40- by 80-Foot Wind Tunnel.

MODELS AND TEST APPARATUS

A summary of parawings tested is presented in table 1. The permeability of the sailcloth for all models was essentially zero. Immediately preceding the test results for each parawing are pattern details and a plot of dimensionless suspension line length as a function of canopy attachment locations. In some cases model photographs are included.

The two parawing mounting methods, tethered and single confluence, are shown in figure 1(a). When tethered, the wing tip and the keel trailing-edge suspension lines were displaced from the main riser attachment point. The suspension line attachment points are shown in figure 1(b).

TESTS

The tests were performed by varying the length of the keel trailing-edge line for several wing-tip line lengths. At each wing-tip line setting, the keel trailing-edge line was shortened until large longitudinal and lateral oscillations occurred. The keel trailing-edge line was then extended until the leading edge collapsed. The length of the suspension lines attached to the main riser was not varied. The tests were made at a free-stream dynamic pressure of 1.0 psf. The 23.9-ft glued single keel and 22.5-ft multiple radial slot parawings were tested on both the tethered and single confluence mounts. The single confluence mount was not used for the other models because the range of line settings was severely limited by high oscillations of the model. Tests were also performed over a range of free-stream forward velocities of 29 to 58 fps ($q = 1.0$ to 4.0 psf) with the model tethered at fixed suspension line settings. This was done for all the models except the 22.7-ft dual keel parawing.

REDUCTION OF DATA

Corrections

The aerodynamic loads of the parawing were measured by the wind-tunnel balance system. The lift and drag data were corrected for the tare of the test apparatus and weight of the model. No corrections have been applied to the data for blockage or the effects of the wind-tunnel walls because estimates of the corrections show them to be negligible.

Accuracy of Data

The various quantities measured in the wind tunnel were accurate within the following limits. The data were obtained by averaging several samples for each data point. Hence the accuracies are for the average values and include errors due to neglected corrections, and recording methods.

Lift	± 10 lb
Drag	± 3 lb
Free-stream dynamic pressure	± 0.1 psf
Control line length	$\pm 1/4$ in.

RESULTS AND DISCUSSION

The basic test results are presented in figures 2 through 7. Each figure contains (1) a description of the model, (2) the effects of keel trailing-edge line length on C_L and L/D , (3) the variation of L/D with C_R , and (4) the effect of q on C_R and L/D (except fig. 6). Data for the 23.9-ft glued single keel model (fig. 4) and 22.5-ft multiple radial slot single keel model (fig. 5) are presented for both the tethered and single confluence mounting methods.

The test results indicate that increasing free-stream dynamic pressure from 1 to 4 psf (velocities from 29 to 58 fps) caused a reduction in L/D for all the parawings except the 15-ft single keel which had no change. The reduction in L/D varied from a small decrement to approximately 0.5.

The results are summarized in figure 8. Figure 8(a) is a summary of the single keel parawings tested and includes results for one of the 5-ft glued single keel parawings of reference 1 (figs. 11 to 16 of the reference). The results for the two dual keel configurations are shown in figure 8(b). Comparison of the 5.0-ft and 23.9-ft glued single keel parawings indicates that for this range of keel lengths canopy size has no significant effect on L/D . (The upward shift in C_R for these two models may be the result of increased rigidity because of the glued construction.) At low C_R values the L/D of the parawing with the multiple radial slots was approximately 0.5 in L/D lower than the other single keel configurations. Figure 8 also shows that the differences in aerodynamic characteristics of the models with different construction techniques is small (within about 0.25 in L/D).

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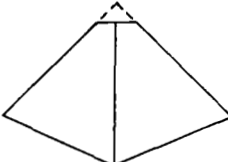
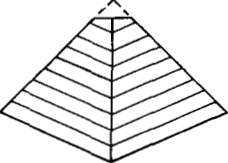
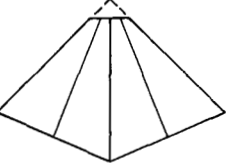
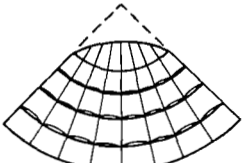
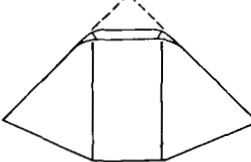
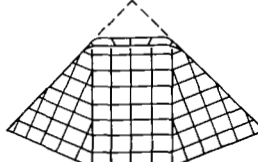
National Aeronautics and Space Administration

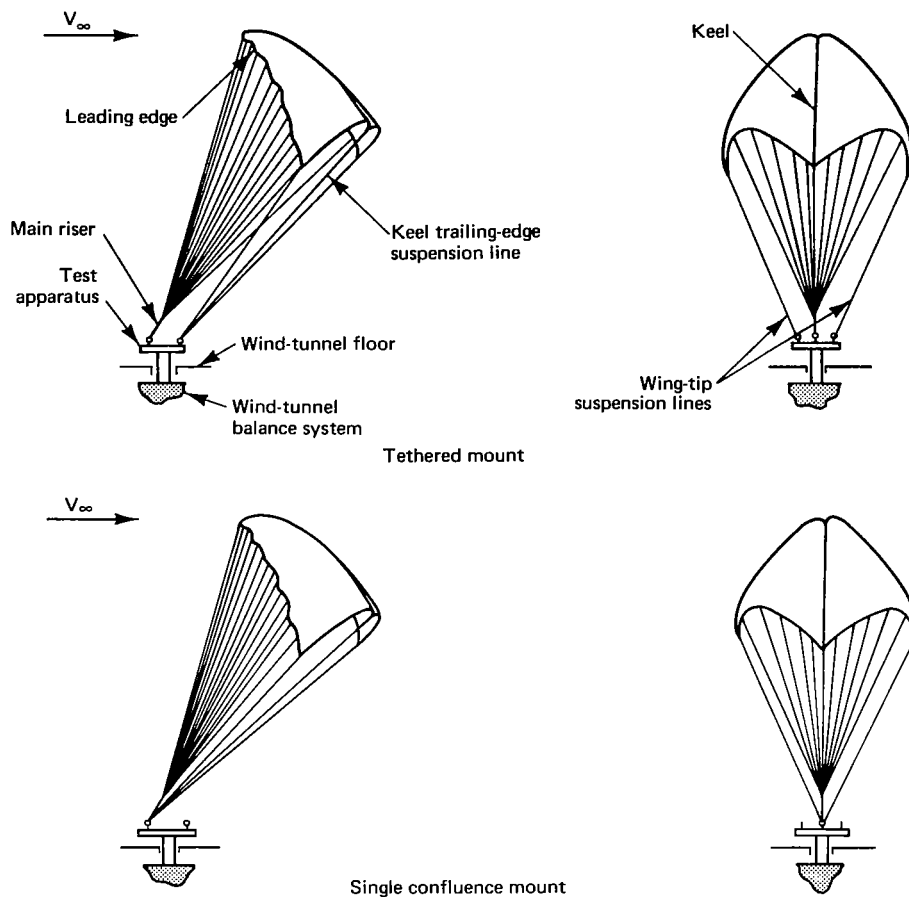
Moffett Field, Calif., 94035, Nov. 19, 1969

REFERENCES

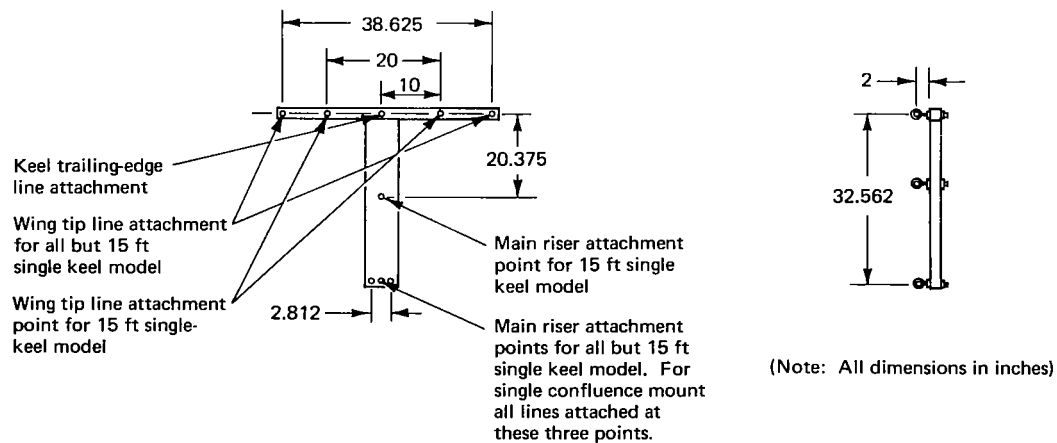
1. Naeseth, Rodger L.; and Fournier, Paul G.: Low-Speed Wind-Tunnel Investigation of Tension-Structure Parawings. NASA TN D-3940, 1967.
2. Bugg, Frank M.; and Sleeman, William C., Jr.: Low-Speed Tests of an All-Flexible Parawing for Landing a Lifting-Body Spacecraft. NASA TN D-4010, 1967.
3. Libbey, Charles E.; Ware, George M.; and Naeseth, Rodger L.: Wind-Tunnel Investigation of the Static Aerodynamic Characteristics of an 18-Foot (5.49-Meter) All-Flexible Parawing. NASA TN D-3856, 1967.
4. Ware, George M.: Wind-Tunnel Investigation of the Aerodynamic Characteristics of a Twin-Keel Parawing. NASA TN D-5199, 1969.

TABLE 1.- SUMMARY OF CONFIGURATIONS

Configuration	Data figure	l_K , ft	S, ft ²	Mounting method	Construction technique	q, psf
 <p>15-ft single keel</p>	2	15	155.12	Tethered	Sewn	1-4
 <p>24-ft single keel</p>	3	24	397.5	Tethered	Sewn with lateral reinforcing tapes	1-4
 <p>23.9-ft glued single keel</p>	4	23.9	396	Tethered and single confluence	Glued	1-4
 <p>22.5-ft multiple radial slot</p>	5	22.5	371	Tethered and single confluence	Sewn	1-4
 <p>22.7-ft dual keel</p>	6	22.7	399.6	Tethered	Sewn	1
 <p>22.7-ft dual keel with lateral and longitudinal reinforcing tapes</p>	7	22.7	399.6	Tethered	Sewn with lateral and longitudinal reinforcing tapes	1-4

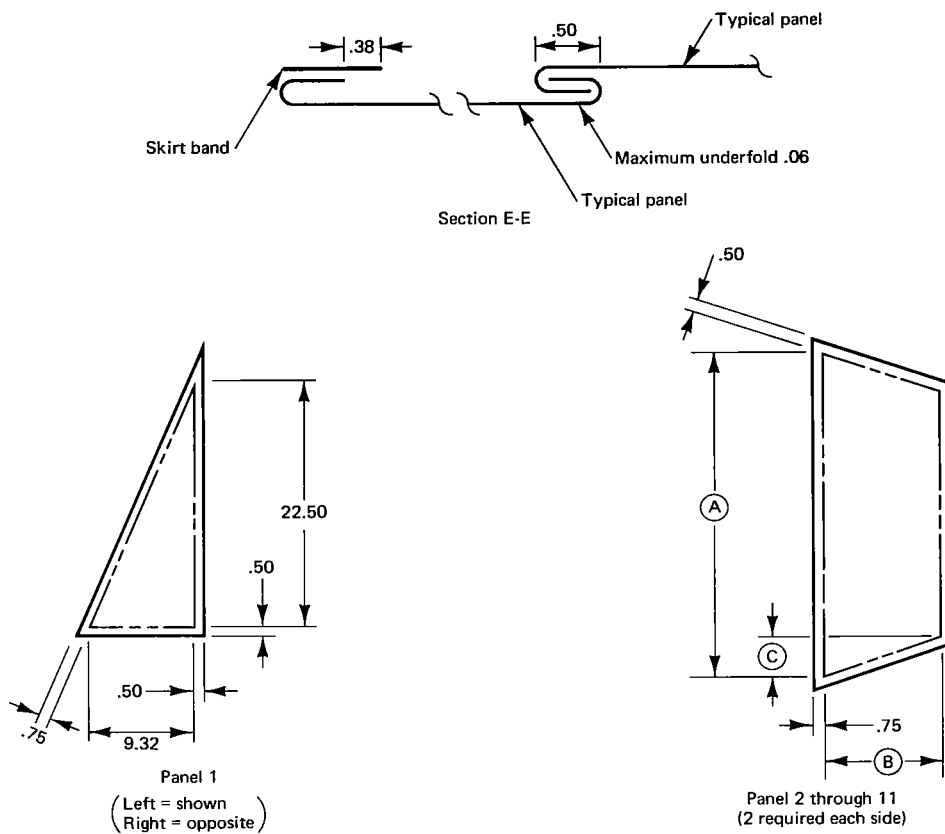


(a) Mounting methods.



(b) Test apparatus.

Figure 1.- Parawing mounting methods and test apparatus.



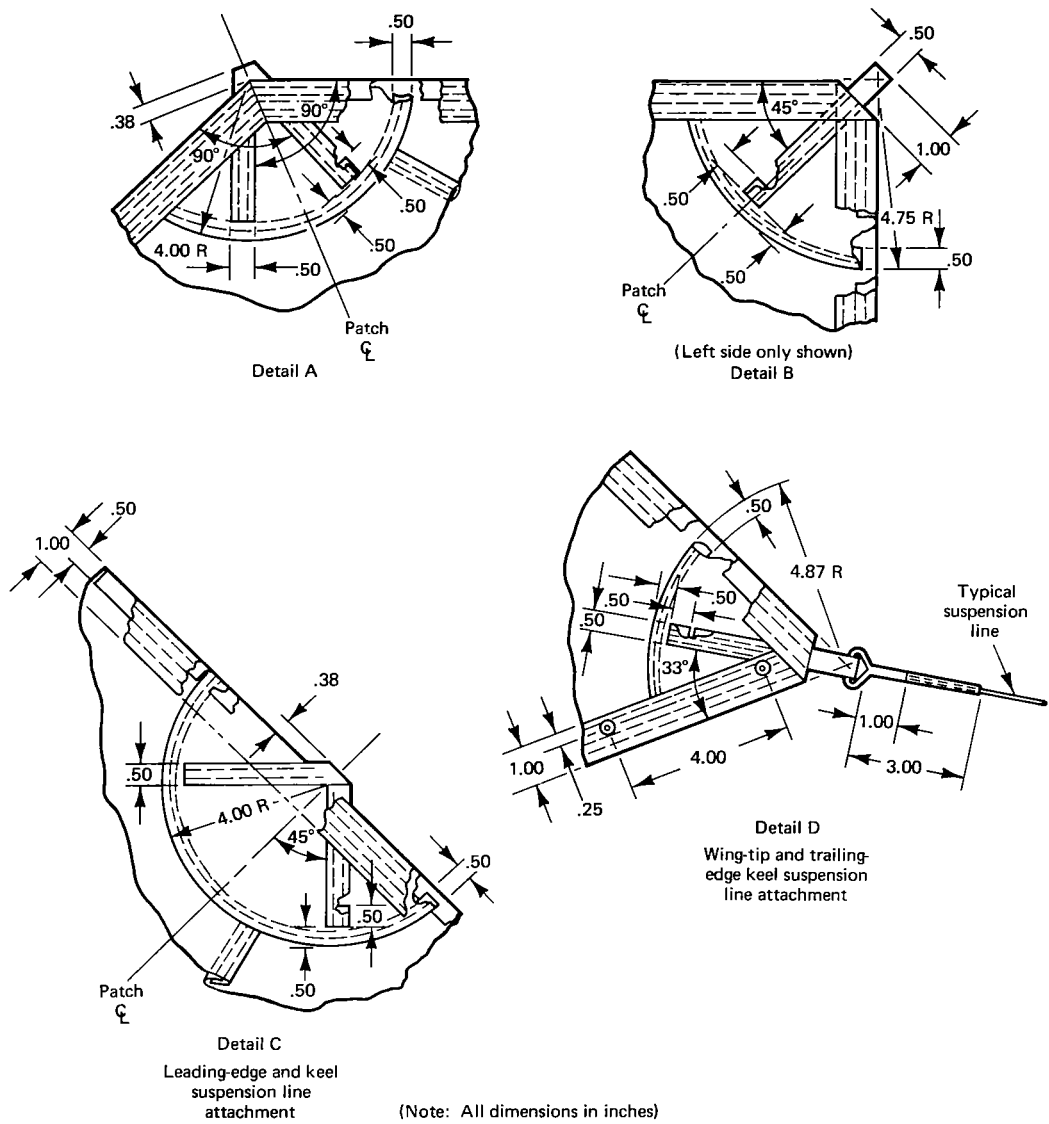
Table

Panel	Dimensions		
	A	B	C
2	34.34	11.95	4.91
3	45.83	13.90	5.75
4	57.32		
5	68.81		
6	80.30		
7	91.79		
8	103.28		
9	114.77		
10	126.25		
11	137.75		

(Notes: Finish dimensions under 15 lb tension;
All dimensions in inches.)

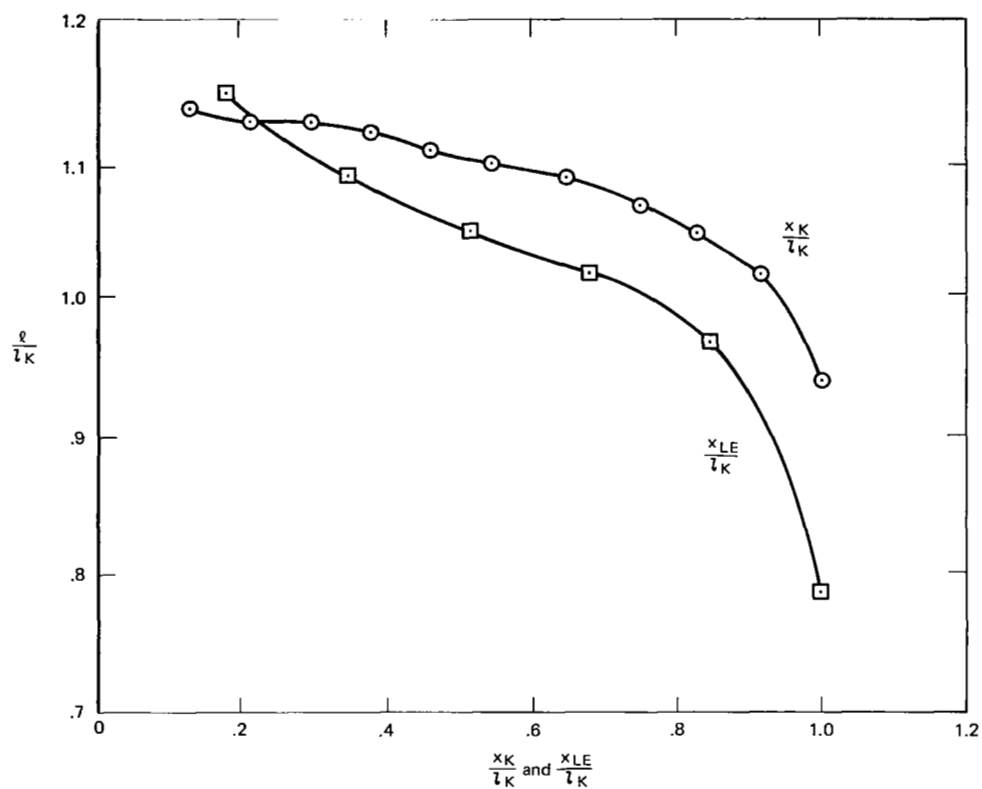
(a) Pattern details - Continued.

Figure 2.- Continued.



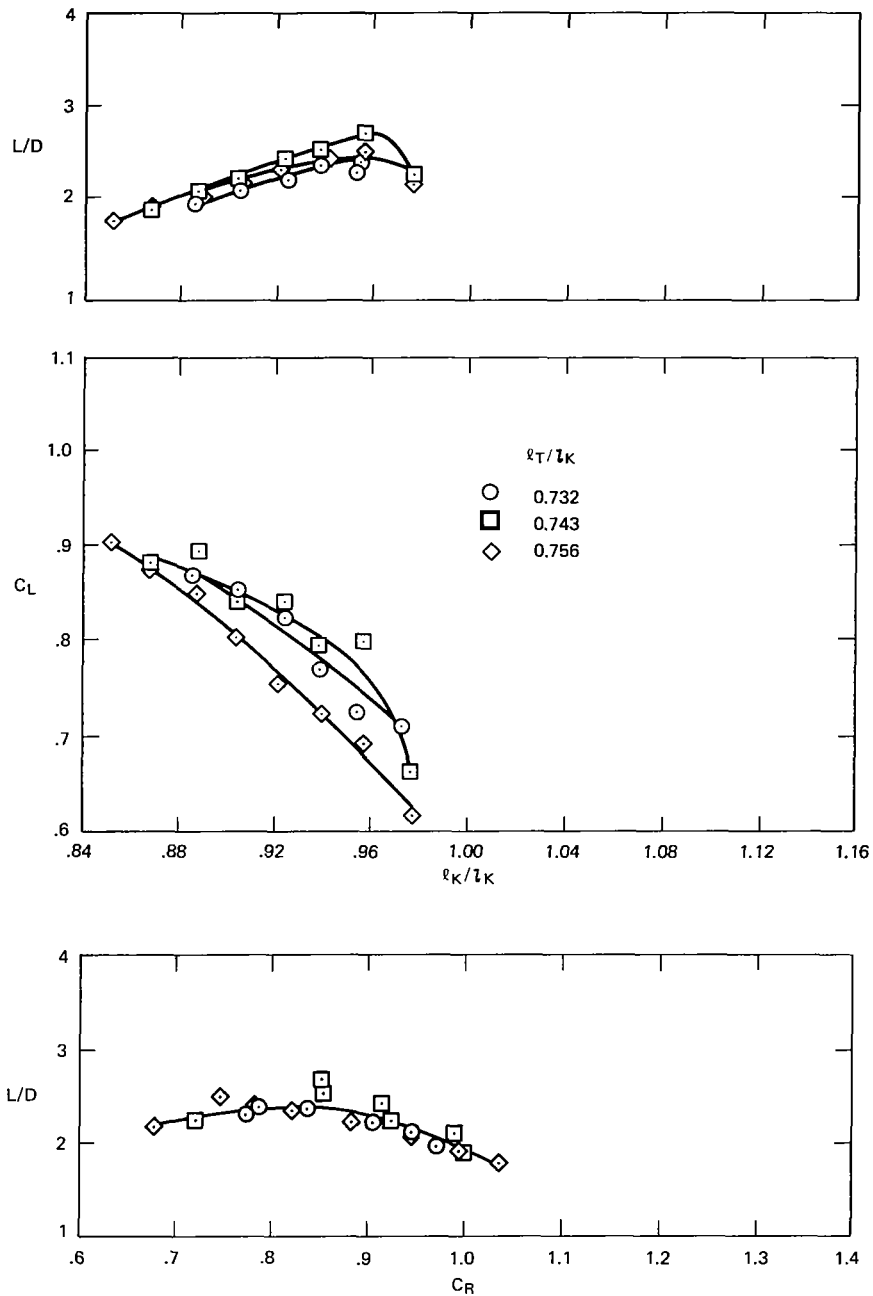
(a) Pattern details - Concluded.

Figure 2.- Concluded.



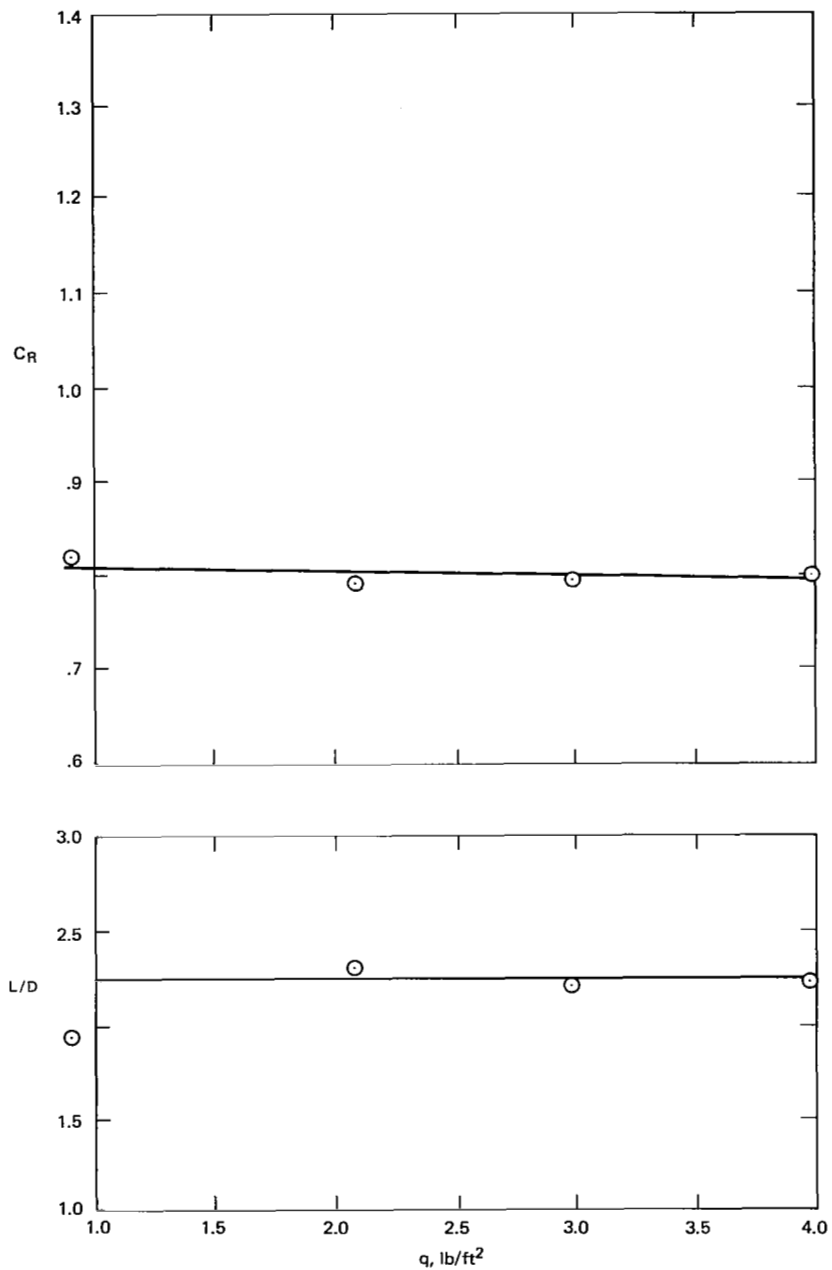
(b) Suspension line lengths as functions of canopy attachment locations.

Figure 2.- Continued.



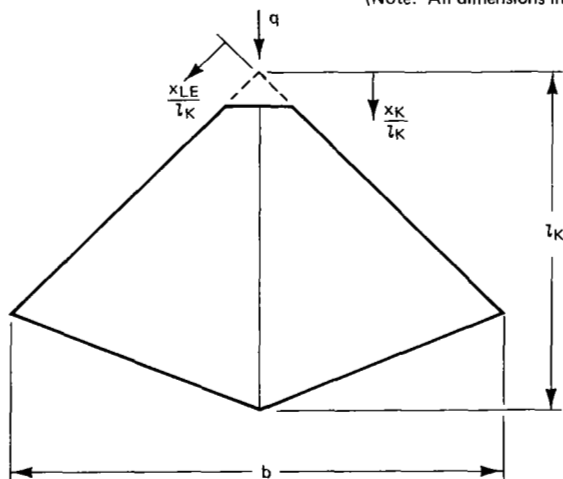
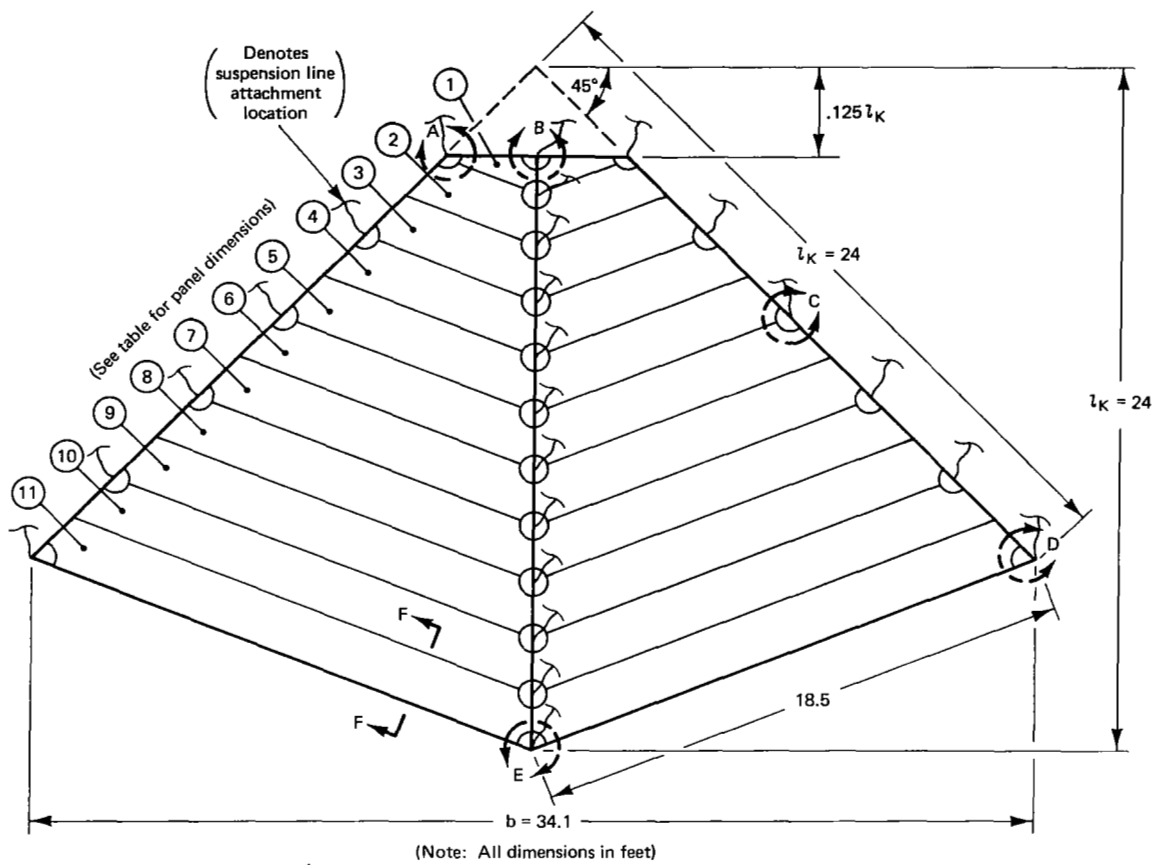
(c) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q \approx 1$ psf.

Figure 2.- Continued.



(d) Resultant force coefficient and lift-drag ratio as functions of free-stream dynamic pressure for $l_T/l_K = 0.744$ and $l_K/l_K = 0.886$.

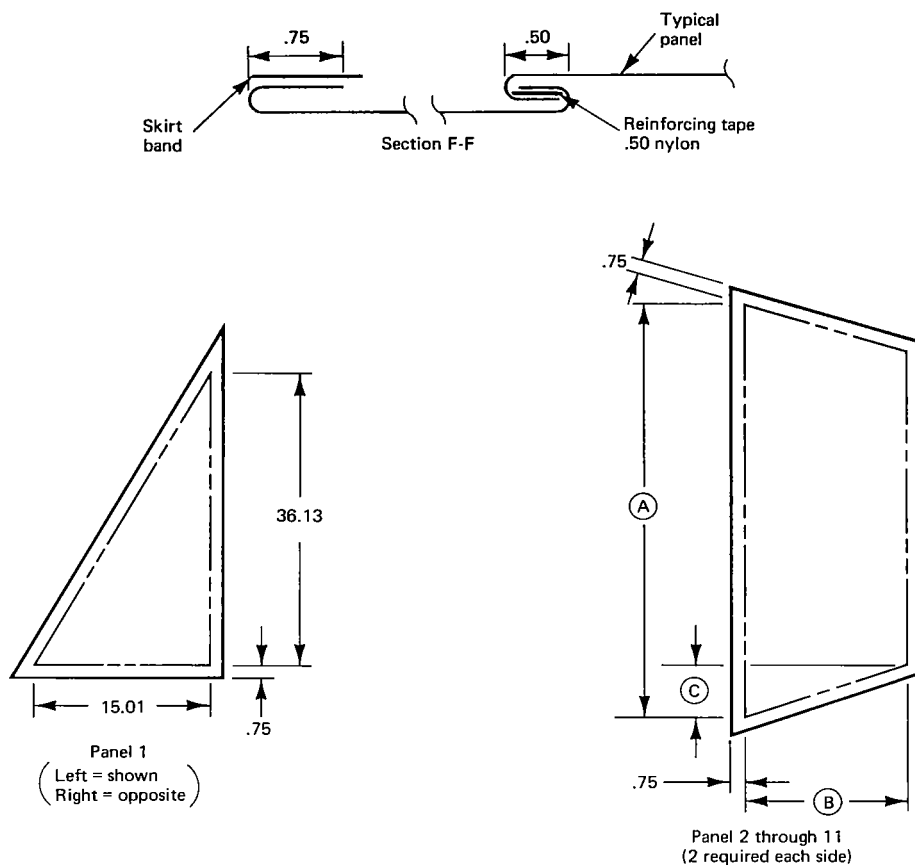
Figure 2.- Concluded.



Canopy area, $S = 397.5 \text{ ft}^2$
 Canopy material = 2.25 oz/yd² nylon
 Suspension lines = 1000 lb dacron cord
 Main riser length = $0.026 l_K$

(a) Pattern details.

Figure 3.- 24-ft single keel parawing.



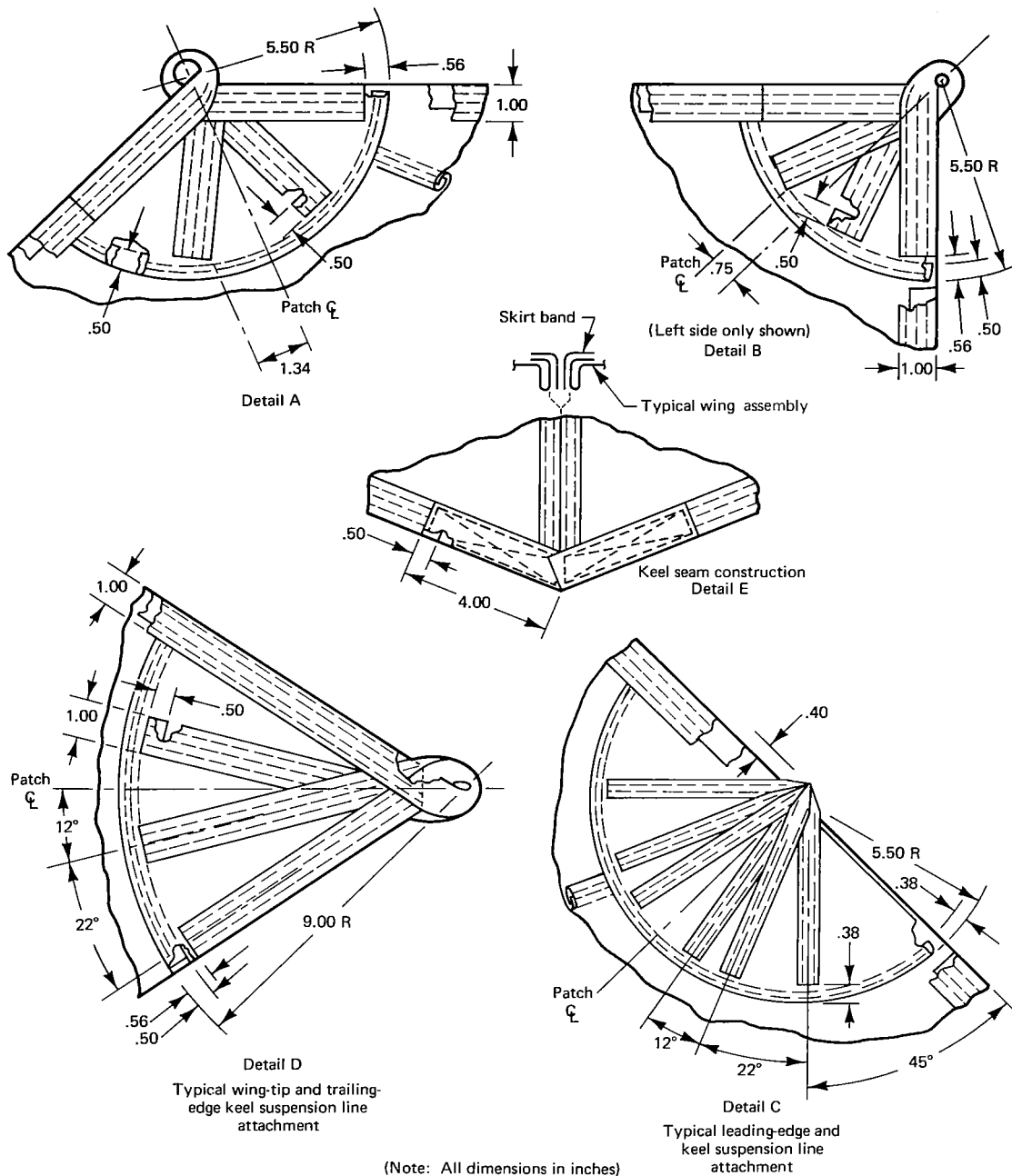
Table

Panel	Dimensions		
	A	B	C
2	55.30	19.53	9.21
3	73.73	22.25	
4	92.17		
5	110.60		
6	129.03		
7	147.46		
8	165.85		
9	184.33		
10	202.76		
11	221.19		

(Note: Finish dimensions under 30 lb tension;
All dimensions in inches.)

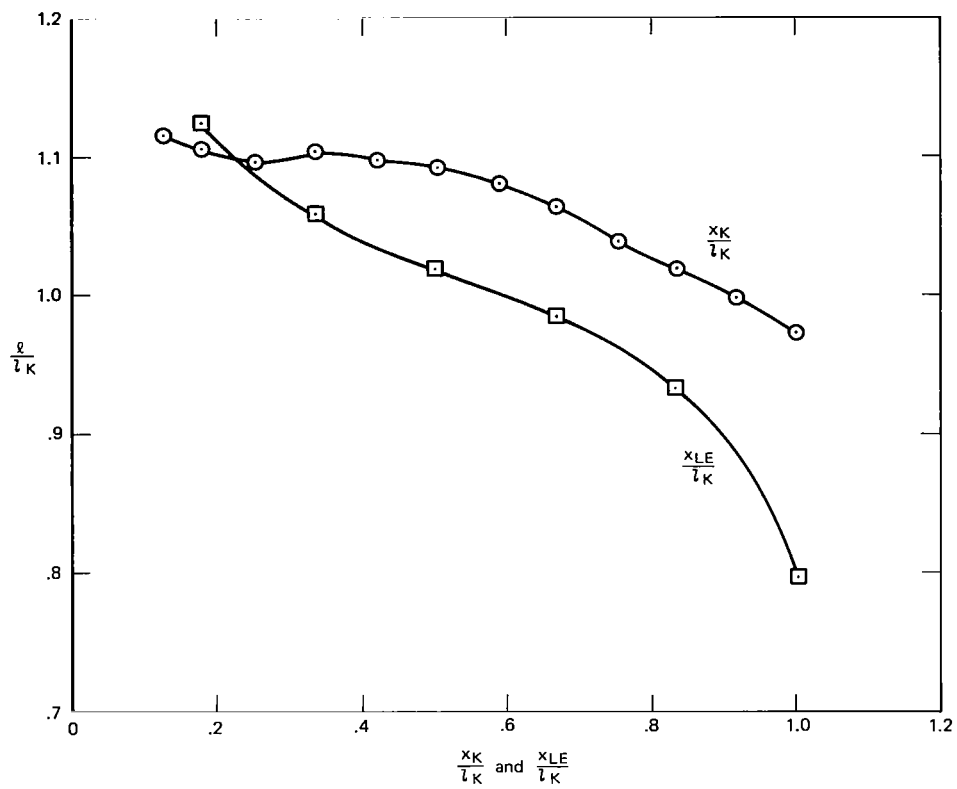
(a) Pattern details - Continued.

Figure 3.- Continued.



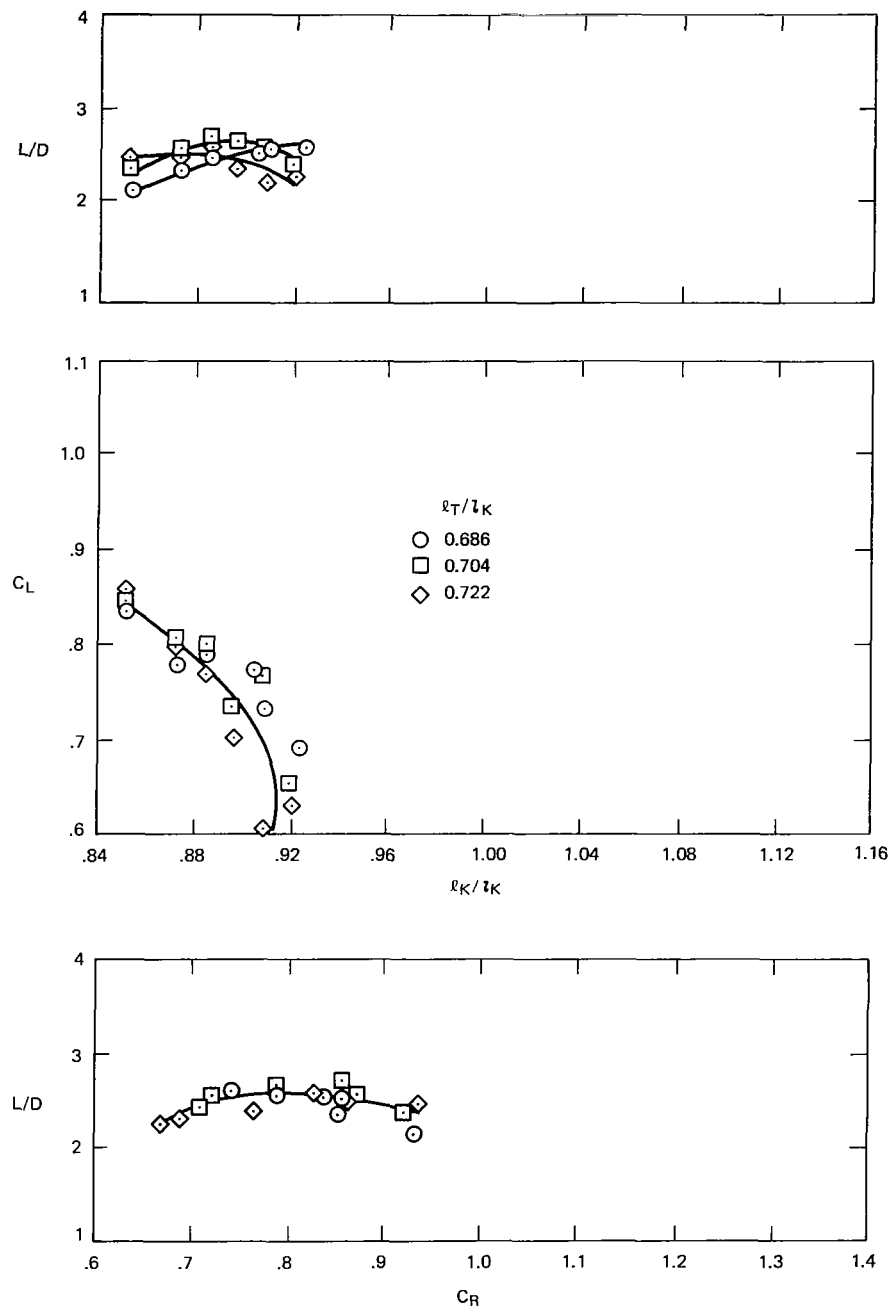
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Figure 3.- Continued.



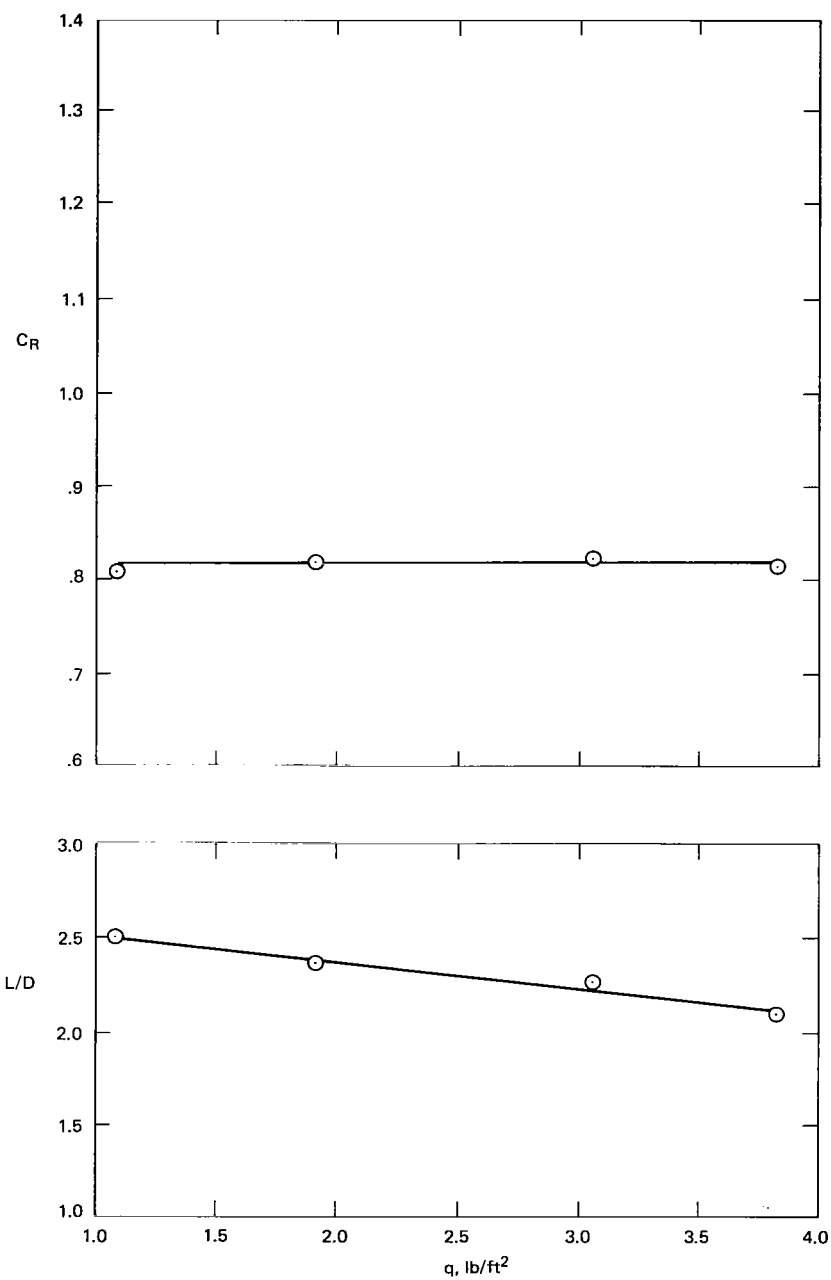
(b) Suspension line lengths as functions of canopy attachment locations.

Figure 3.- Continued.



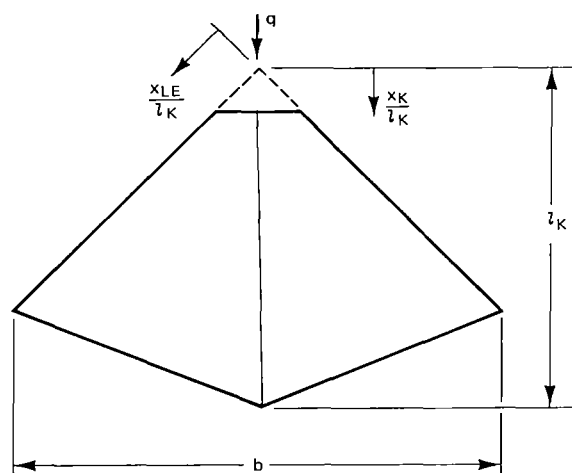
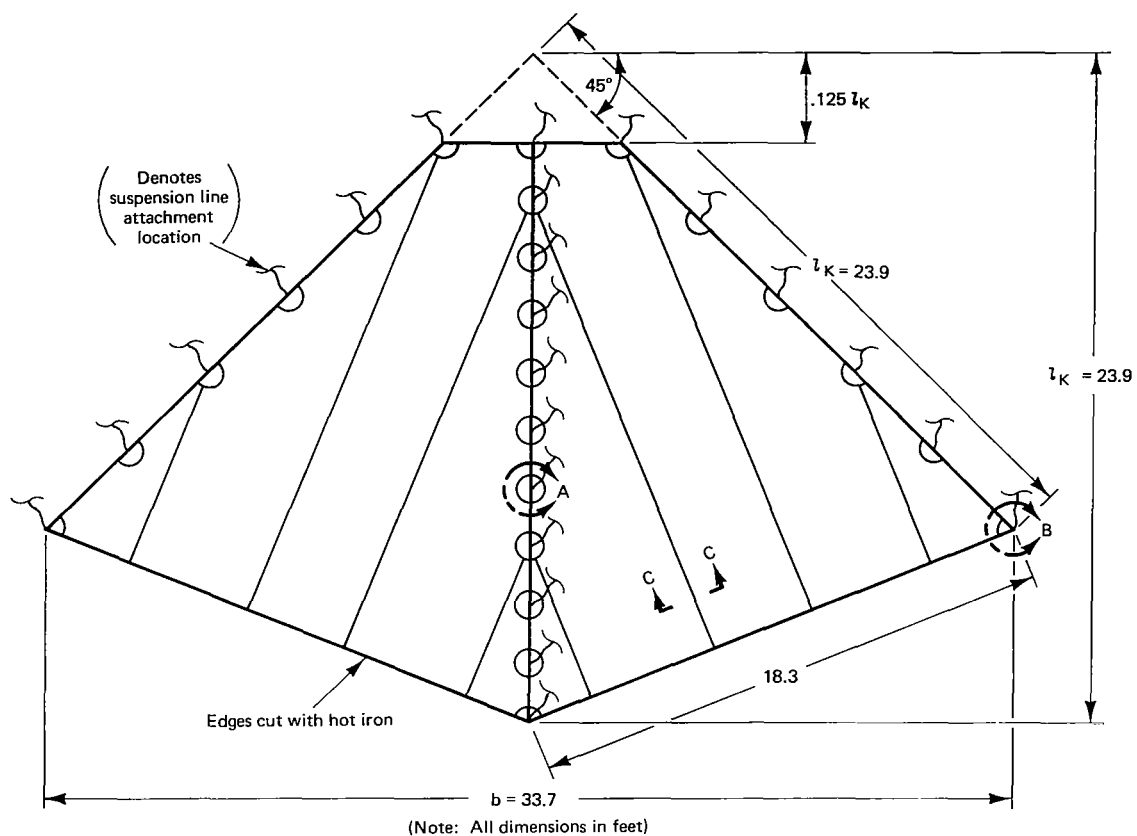
(c) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q = 1$ psf.

Figure 3.- Continued.



(d) Resultant force coefficient and lift-drag ratio as functions of free-stream dynamic pressure for $\ell_T/\ell_K = 0.703$ and $\ell_K/\ell_K = 0.911$.

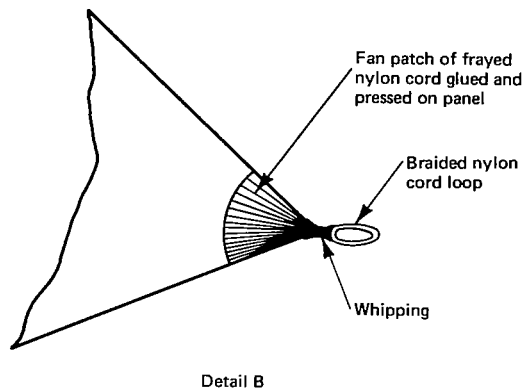
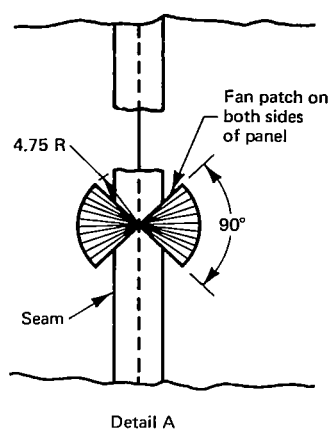
Figure 3.- Concluded.



Canopy area, $S = 396 \text{ ft}^2$
 Canopy material = 2.2 oz/yd² calendered rip-stop nylon
 Suspension lines = 500 lb dacron cord
 Main riser length = $0.026 l_K$

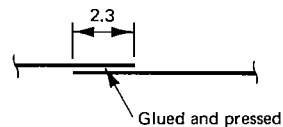
(a) Pattern details.

Figure 4.- 23.9-ft glued single keel parawing.

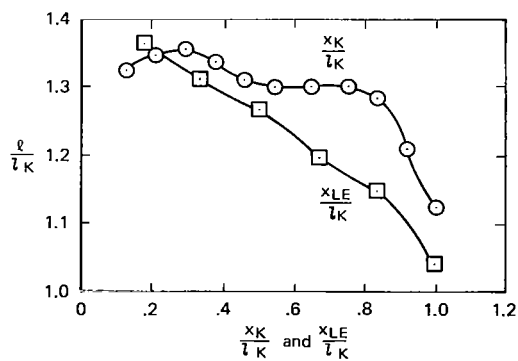


(a)

(Note: All dimensions in inches)

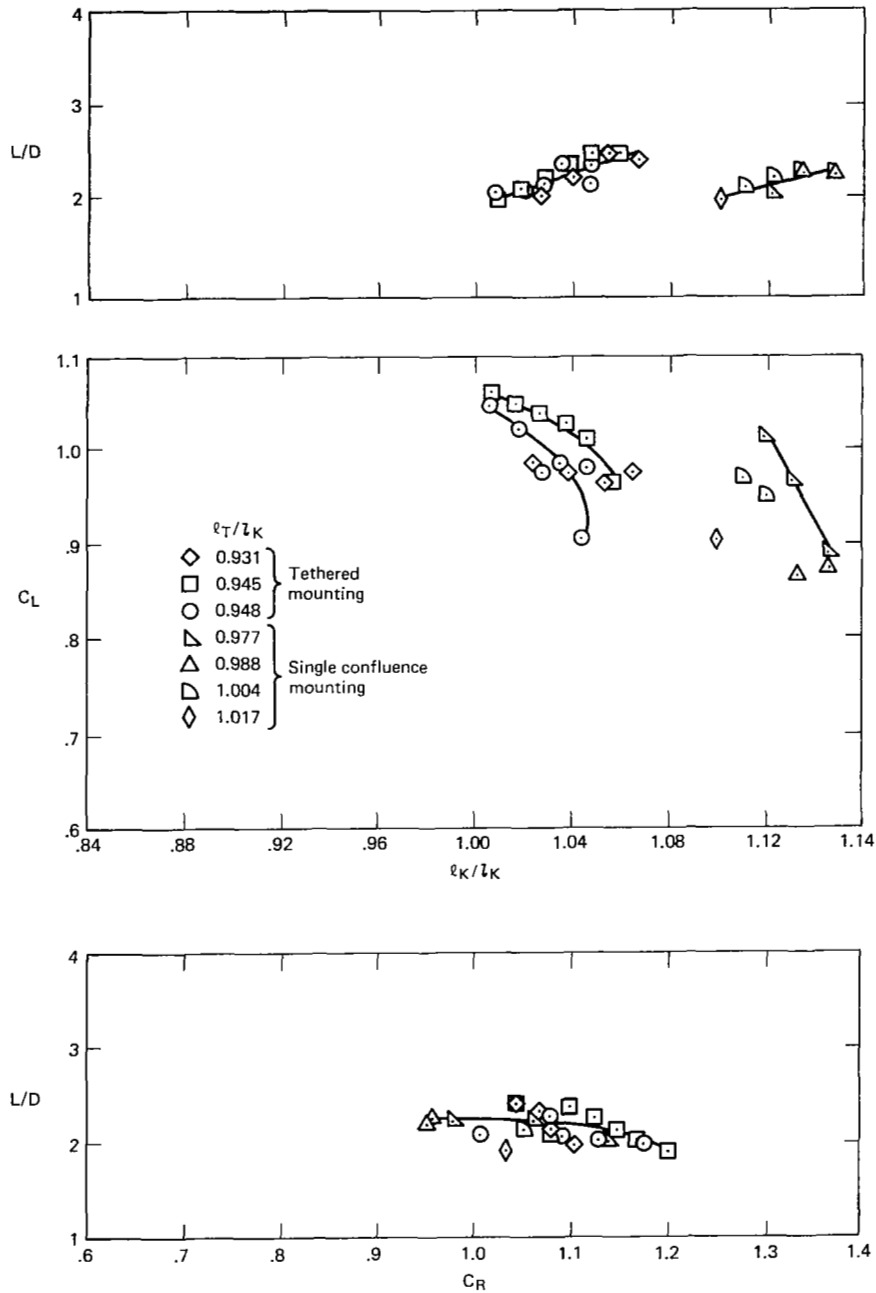


(b)



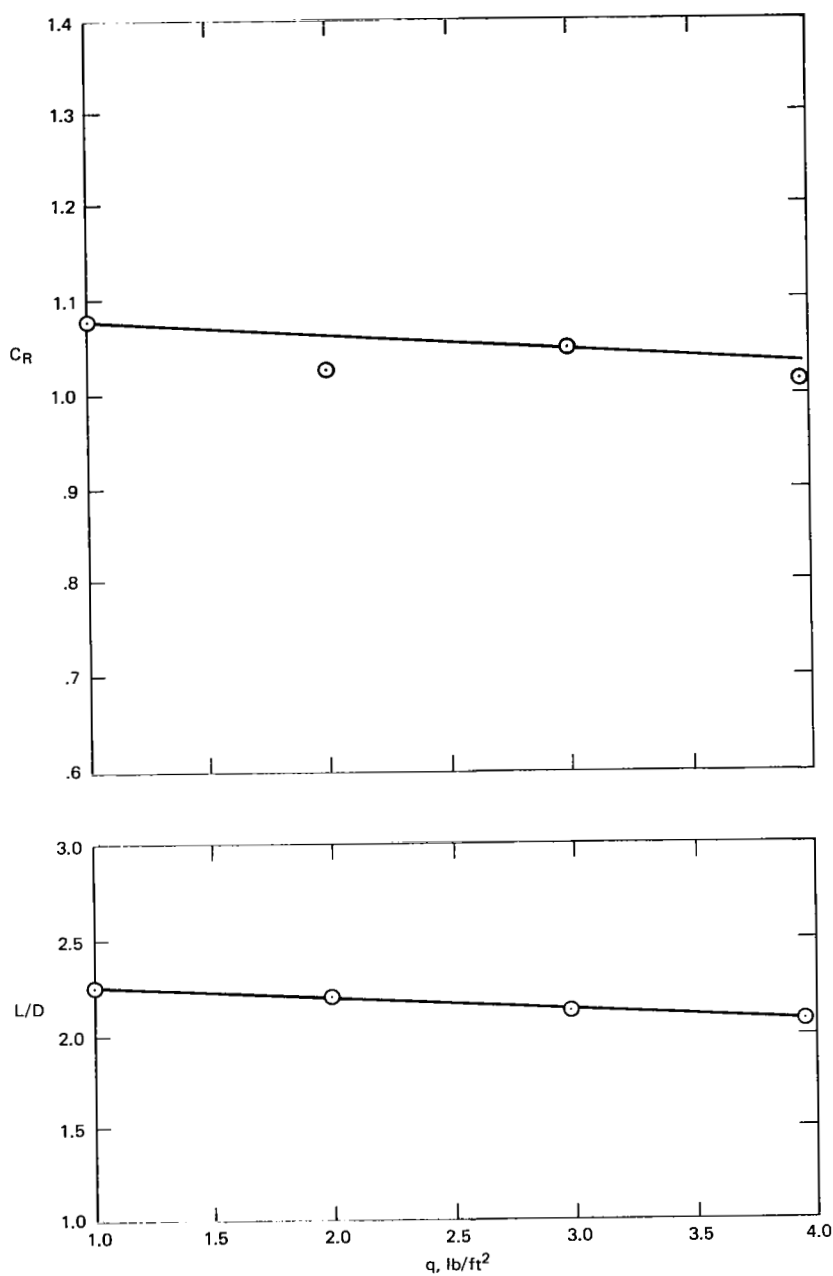
- (a) Pattern details - Concluded.
 (b) Photograph of parawing in wind tunnel.
 (c) Suspension line lengths as functions of canopy attachment locations.

Figure 4.- Continued.



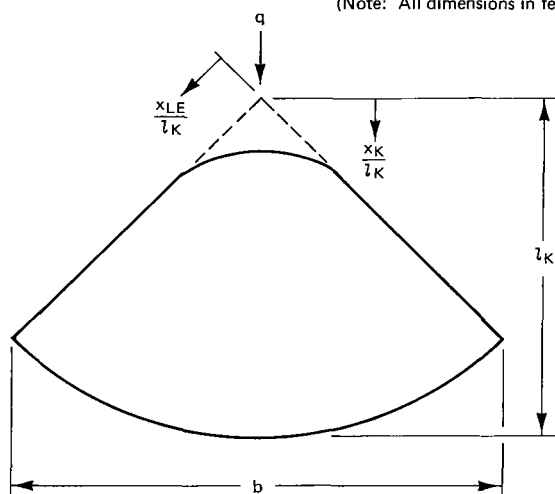
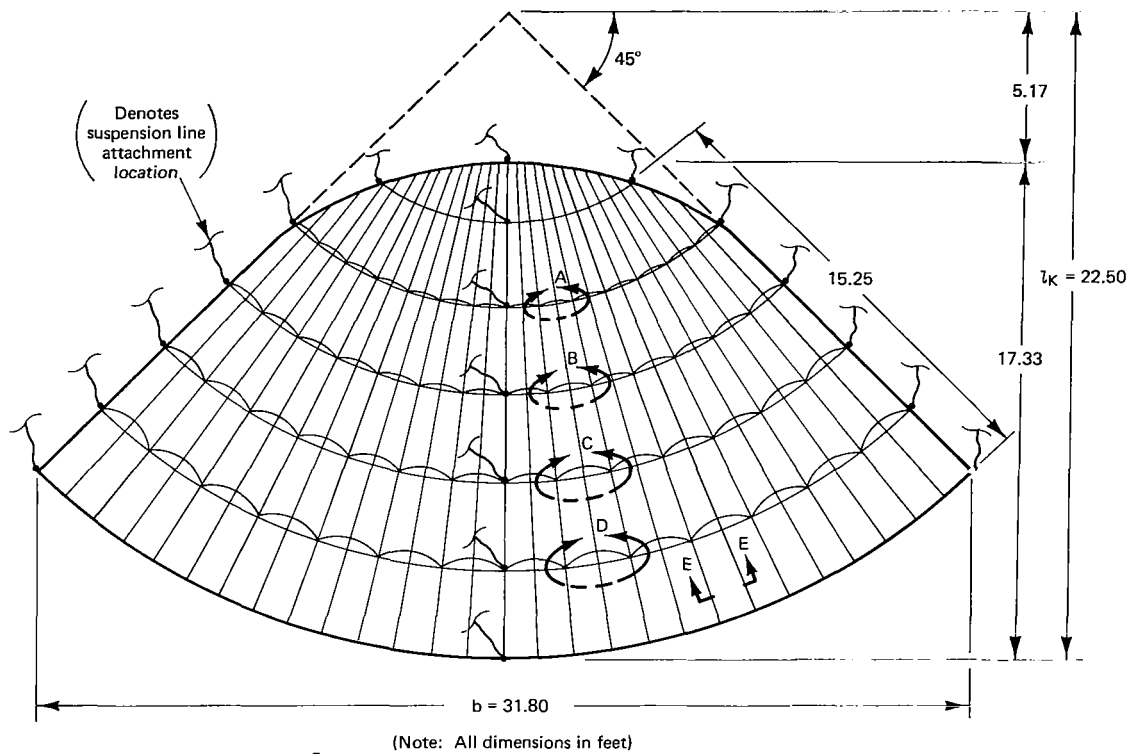
(d) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q = 1$ psf.

Figure 4.- Continued.



(e) Resultant force coefficient and lift-drag ratio as functions of free-stream dynamic pressure for $l_T/l_K = 0.944$ and $l_K/l_K = 1.038$; tethered mounting.

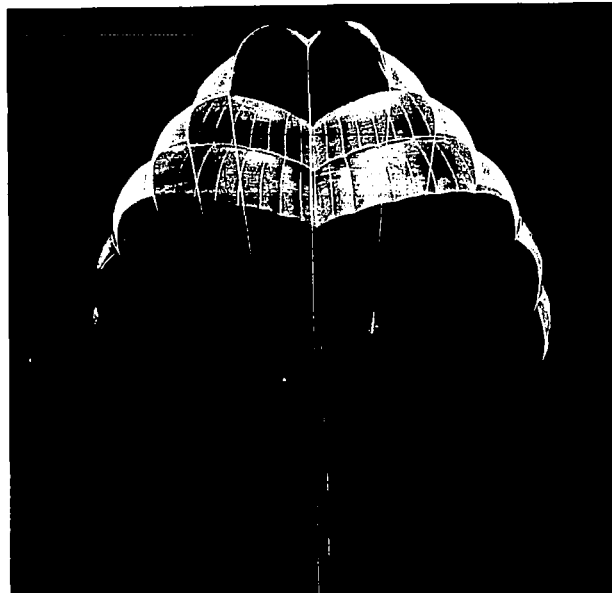
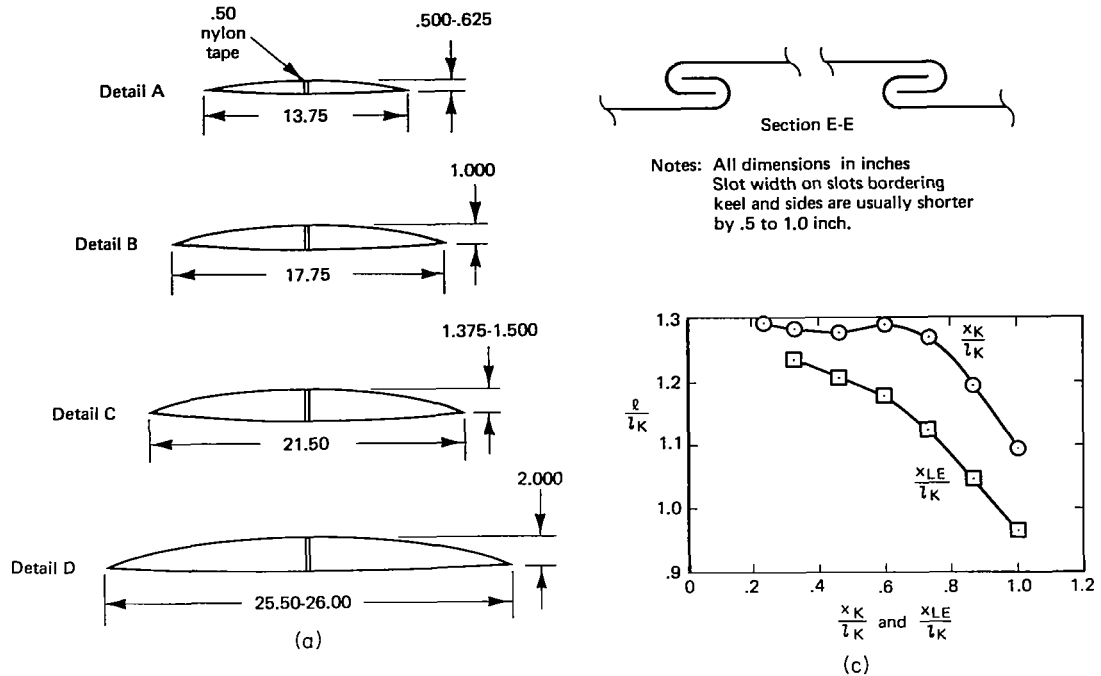
Figure 4.- Concluded.



Canopy area, $S = 371 \text{ ft}^2$
 Canopy material:
 Front 2 panels = 2.25 oz/yd² coated nylon
 Aft 4 panels = 2.25 oz/yd² 20–30% porosity nylon
 Suspension line material = 750 lb nylon cord
 Main riser length = $0.028 l_K$

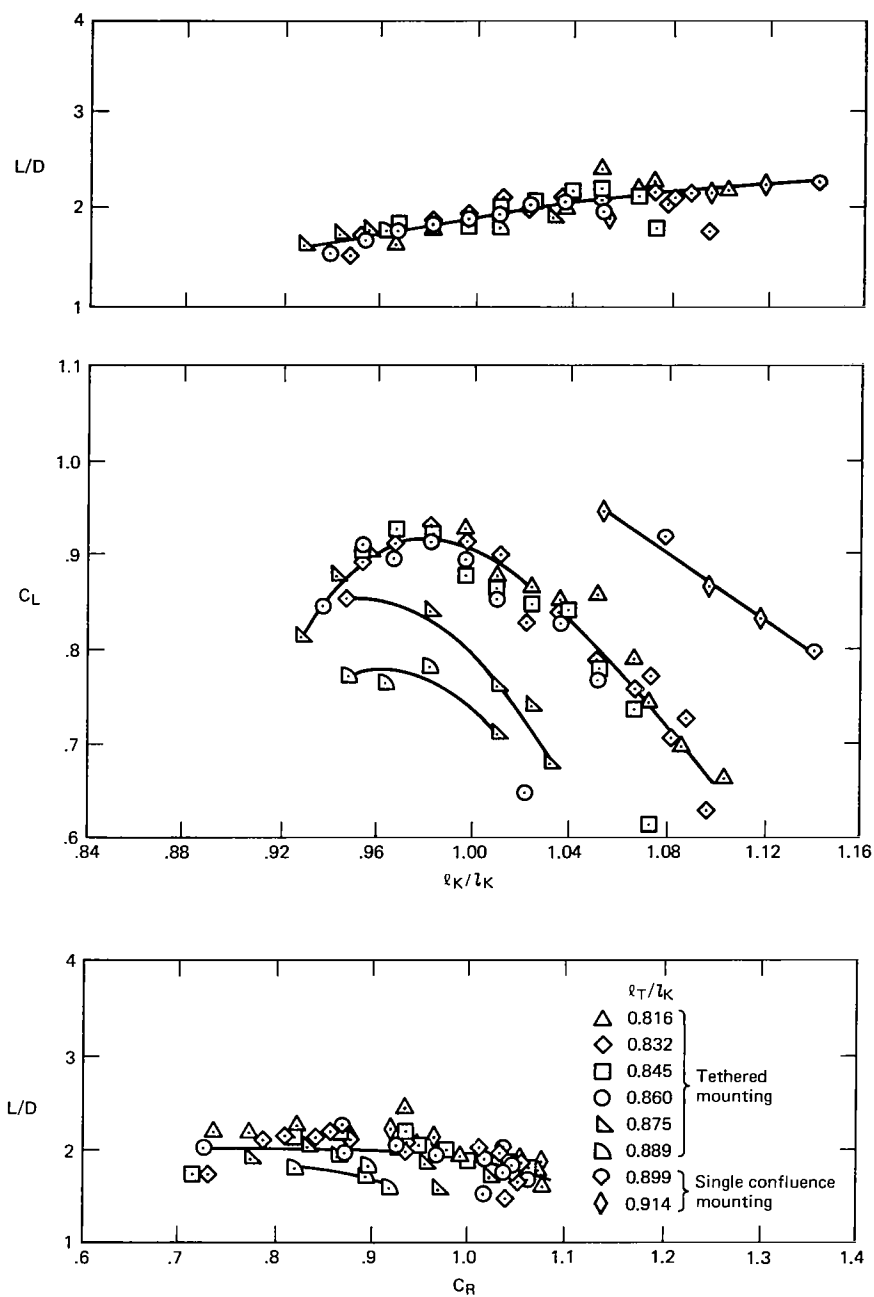
(a) Pattern details.

Figure 5.- 22.5-ft multiple radial slot parawing.



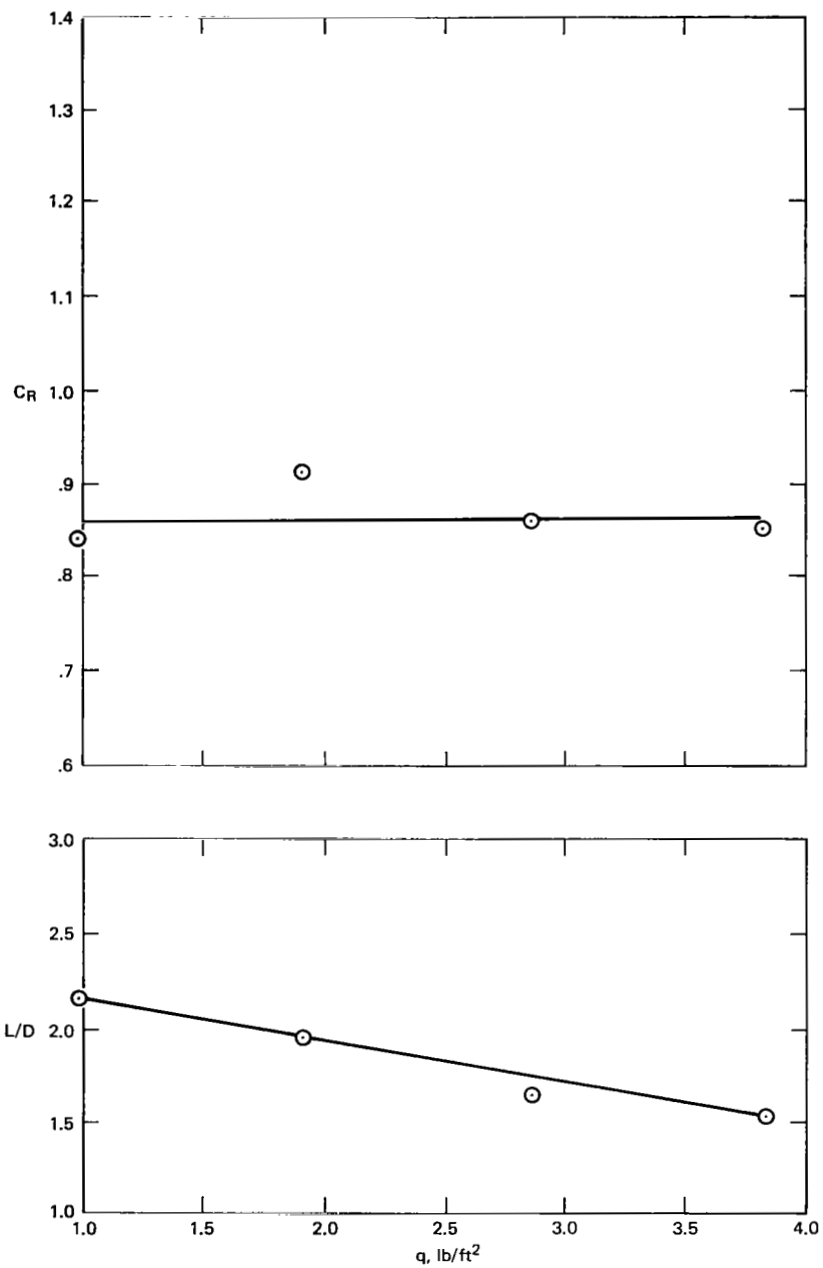
(a) Pattern details - Concluded.
 (b) Photograph of parawing in wind tunnel.
 (c) Suspension line lengths as functions of canopy attachment locations.

Figure 5.- Continued.



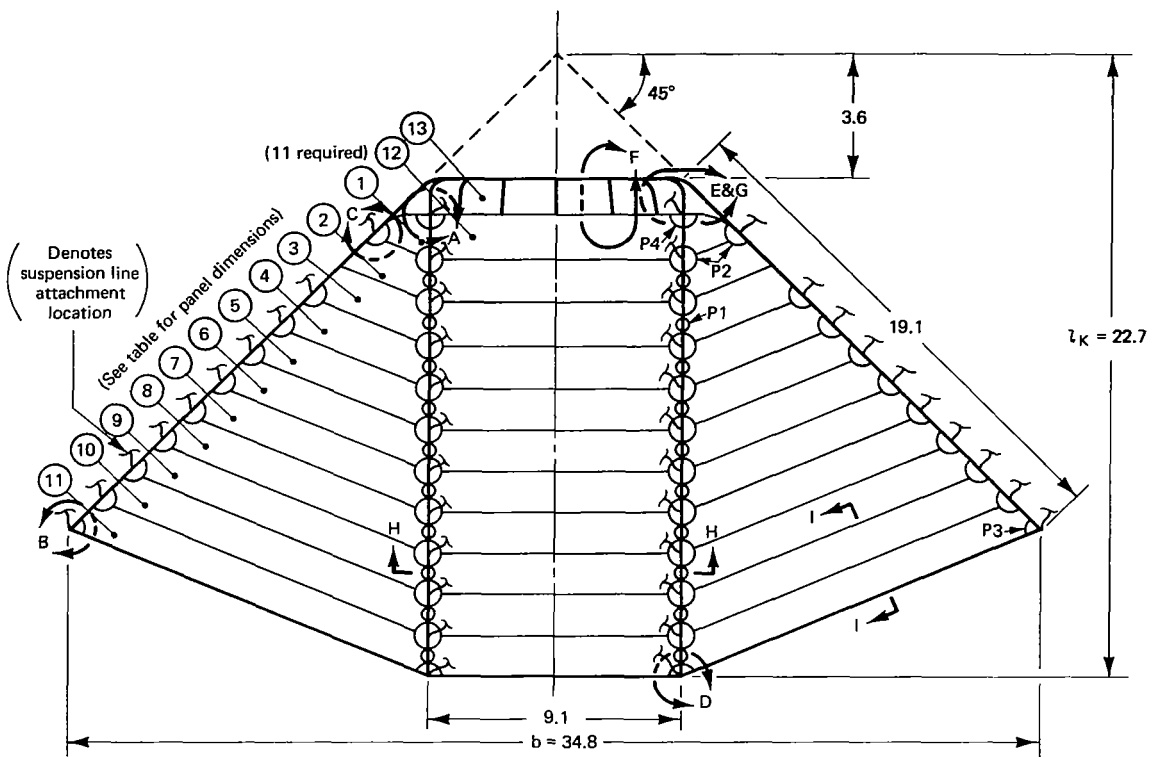
(d) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q = 1$ psf.

Figure 5.- Continued.

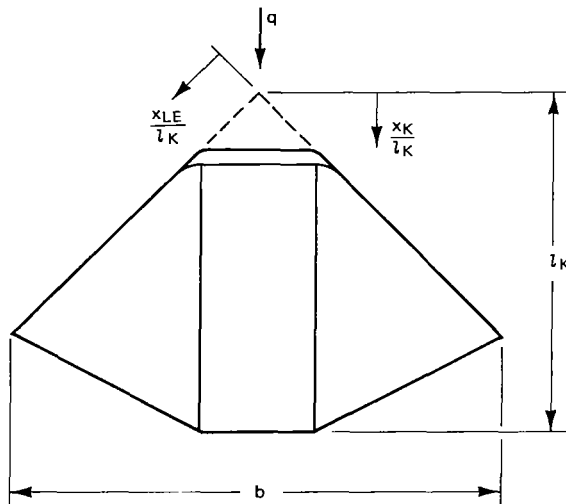


(e) Resultant force coefficient and lift-drag ratio as functions of free-stream dynamic pressure for $\ell_T/\ell_K = 0.845$ and $\ell_K/\ell_K = 1.04$; tethered mounting.

Figure 5.- Concluded.



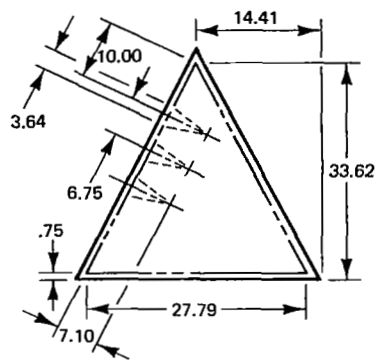
(Note: All dimensions in feet)



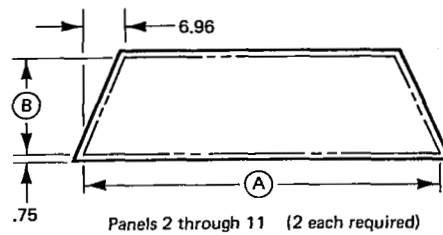
Canopy area, $S = 399.6 \text{ ft}^2$
 Canopy material = 2.25 oz/yd² nylon
 Suspension lines = 1000 lb dacron
 Main riser length = $0.051 l_K$

(a) Pattern details.

Figure 6.- 22.7-ft dual keel parawing.

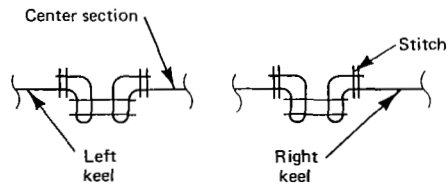


Panel 1 (2 required)
Detail E

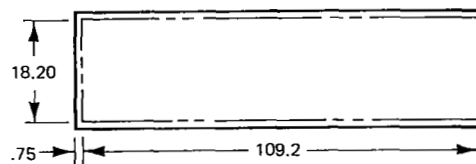


Table

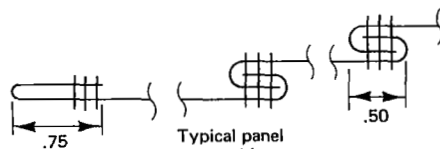
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4	69.58	
5	83.51	
6	97.44	
7	111.36	
8	125.29	
9	139.22	
10	153.15	
11	167.08	



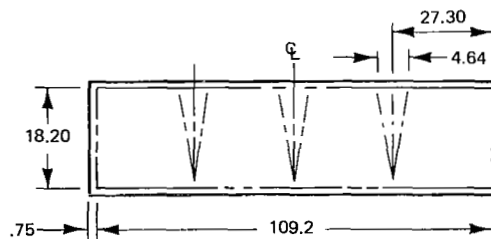
Canopy assembly
Section H-H



Panel 12 (11 required)



Typical panel
assembly
Section I-I

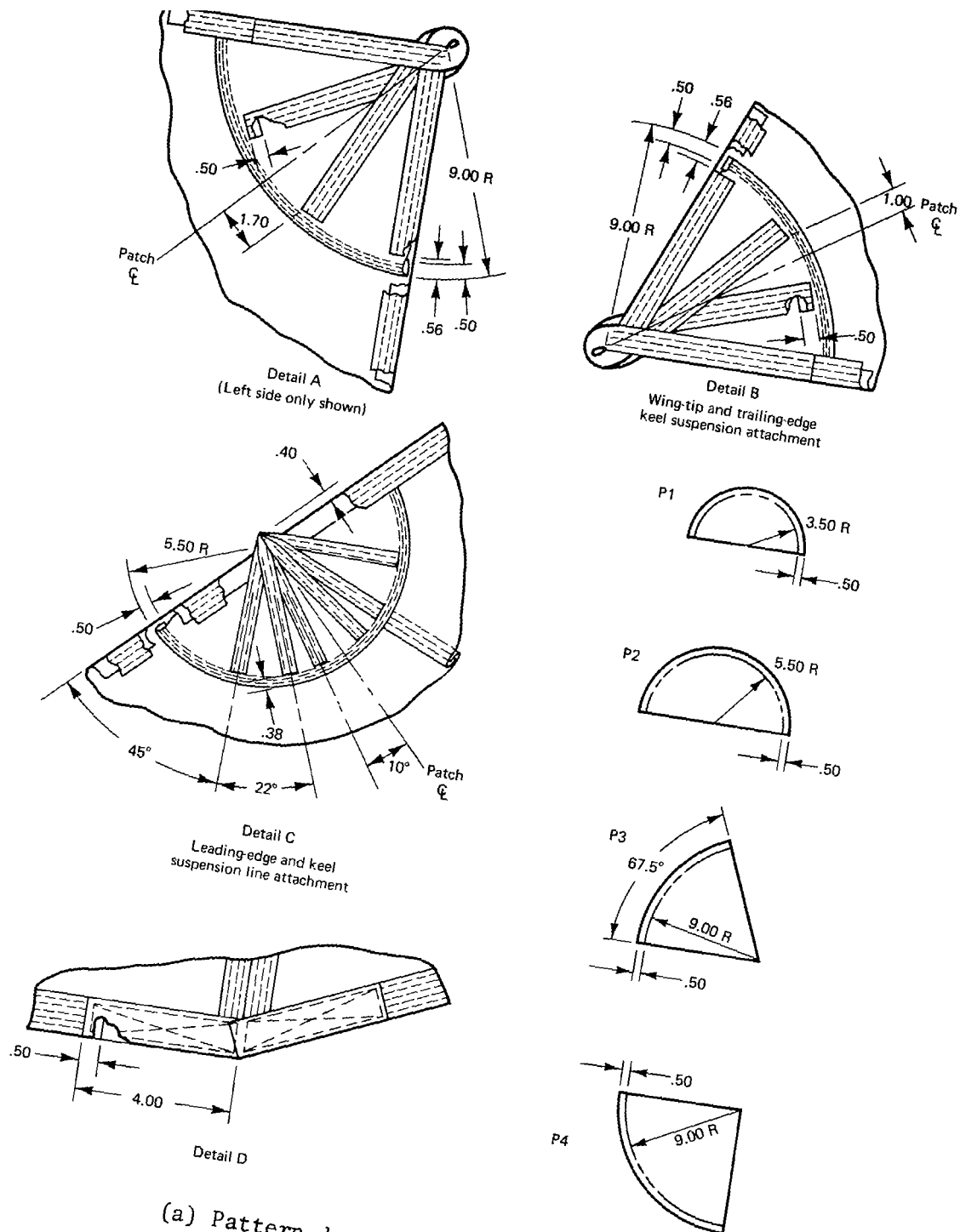


Panel 13 (1 required)

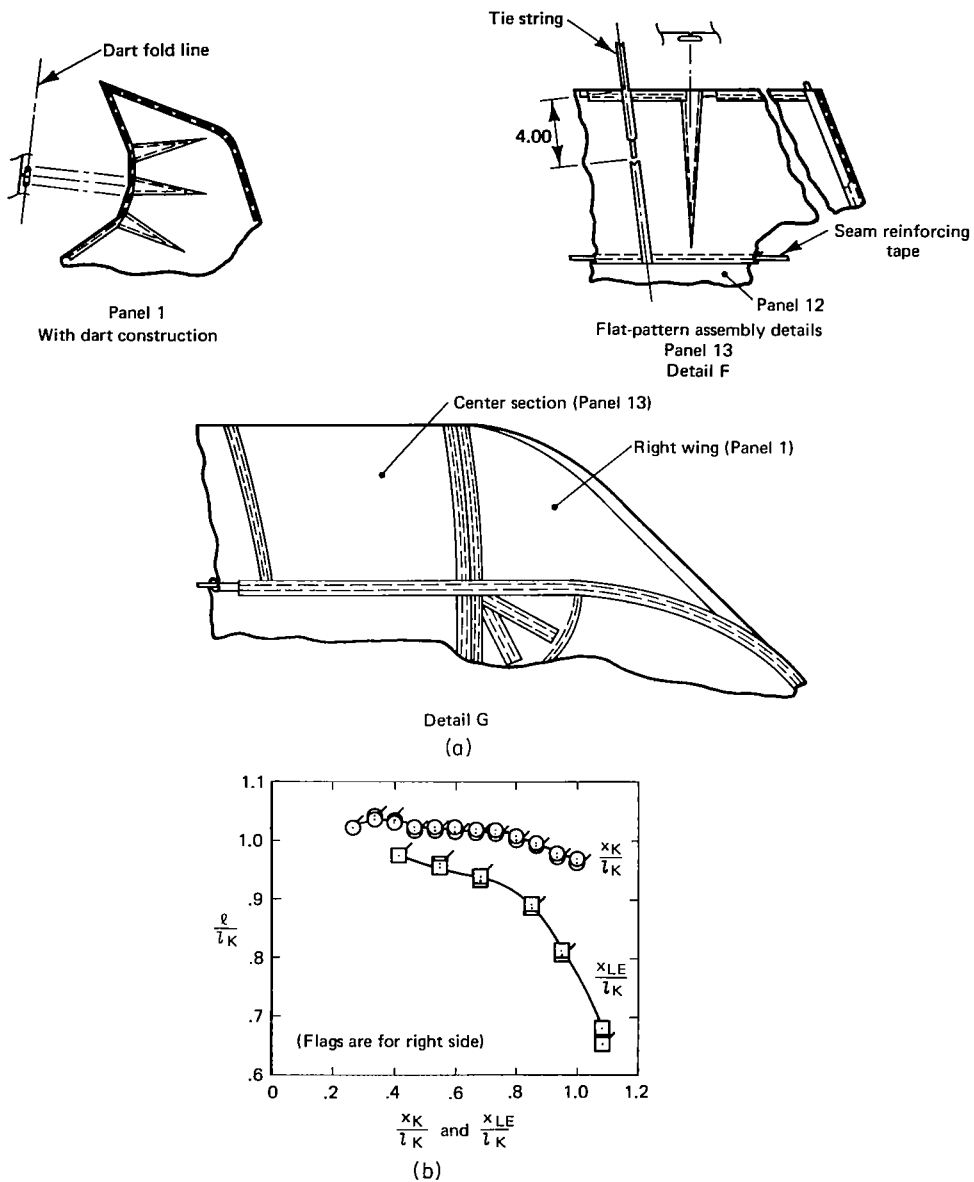
(Note: All dimensions in inches)

(a) Pattern details - Continued.

Figure 6.- Continued.

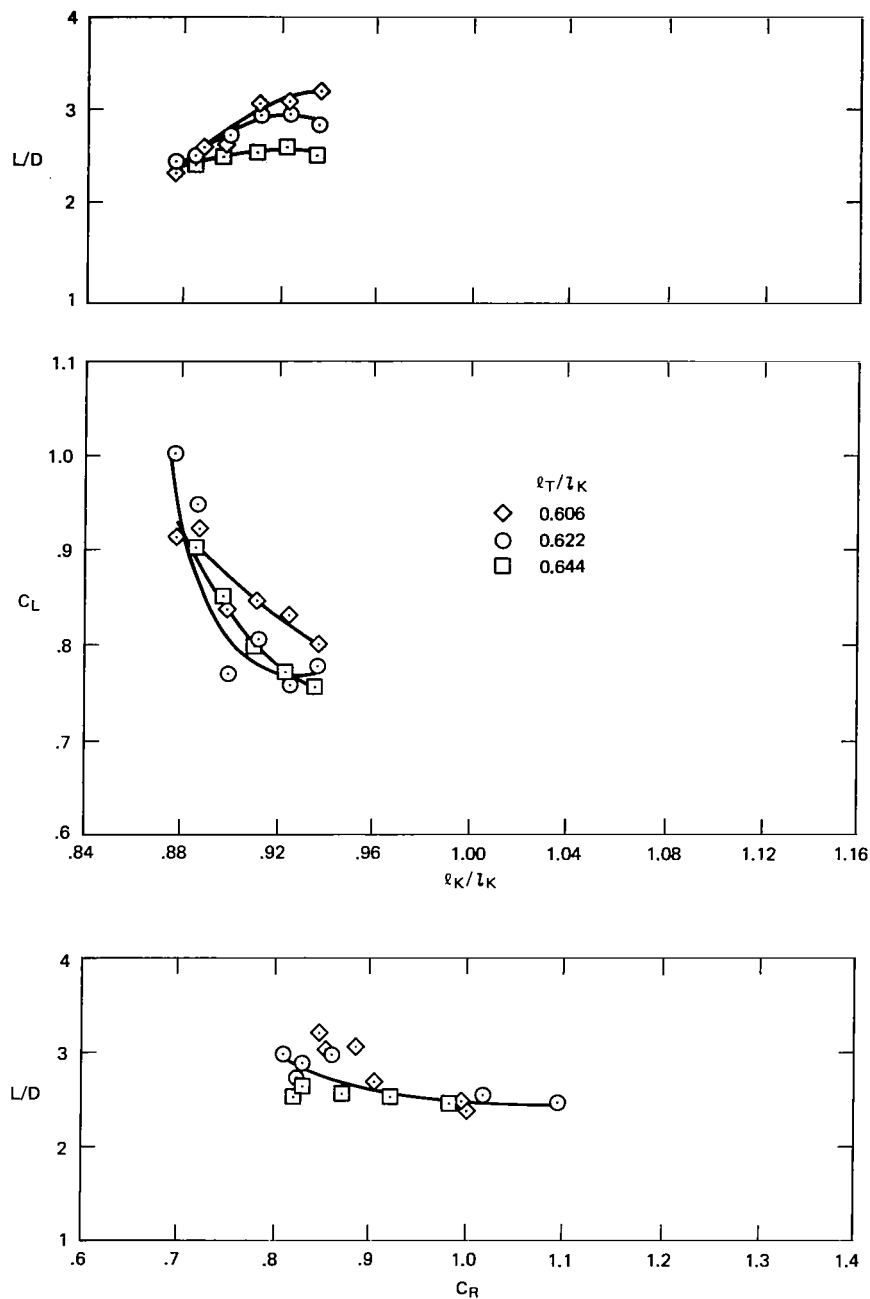


(a) Pattern details - Continued.
 Figure 6.- Continued.



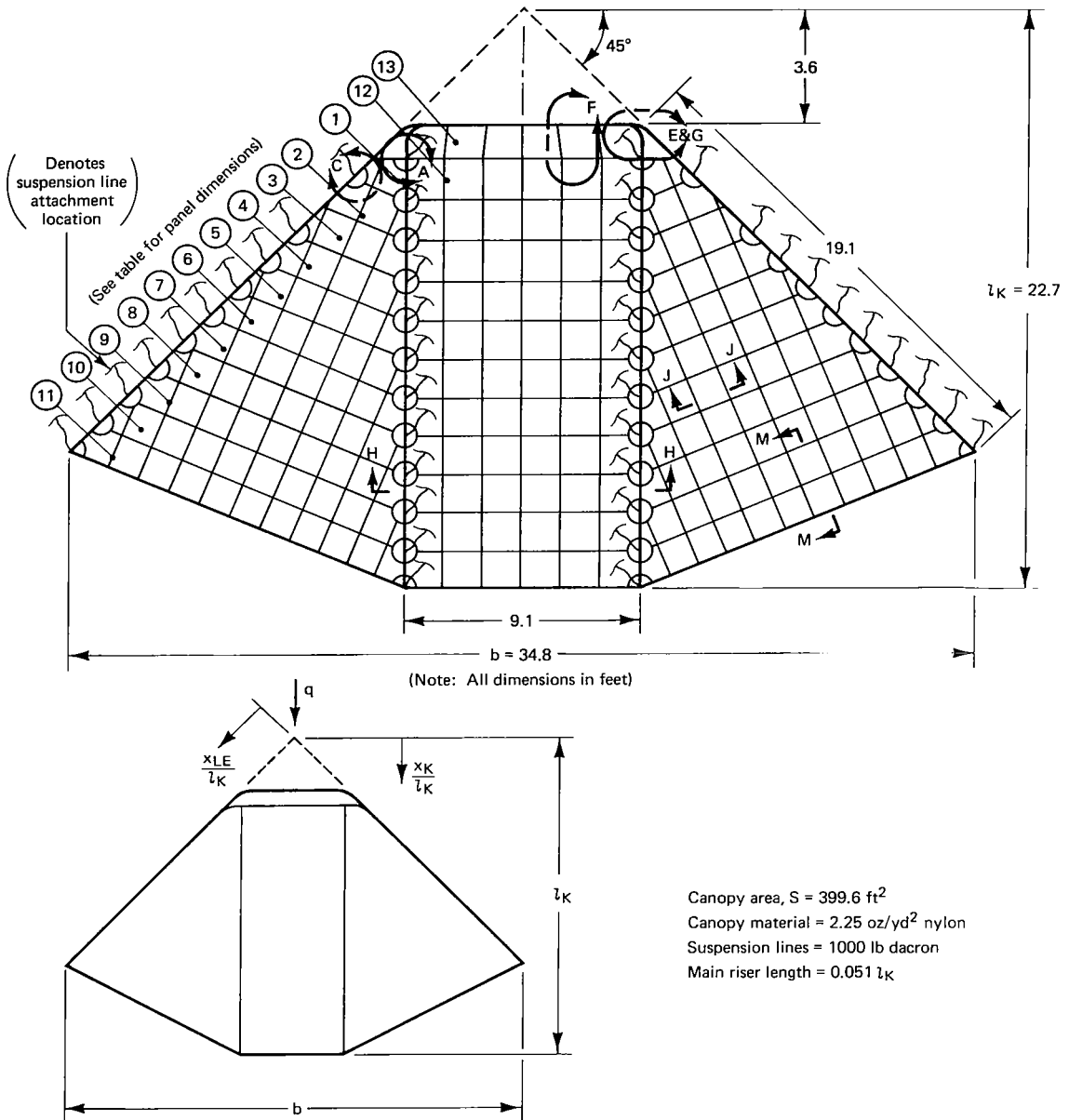
- (a) Pattern details - Concluded.
 (b) Suspension line lengths as functions of canopy attachment location.

Figure 6.- Continued.



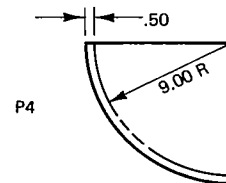
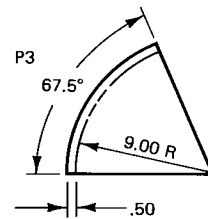
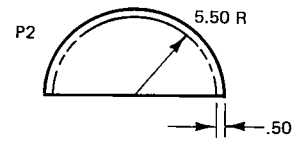
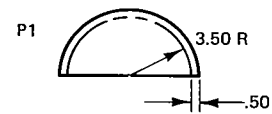
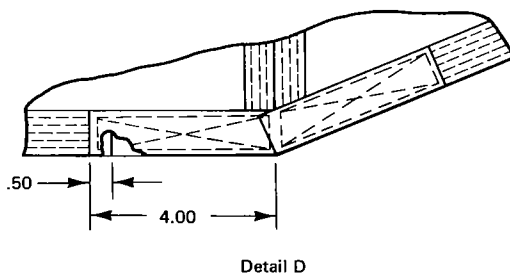
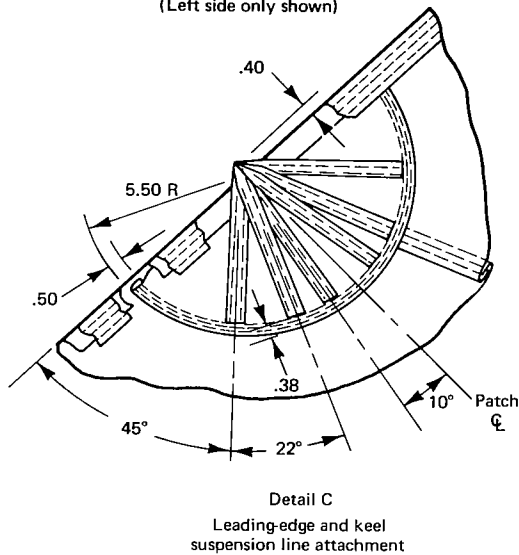
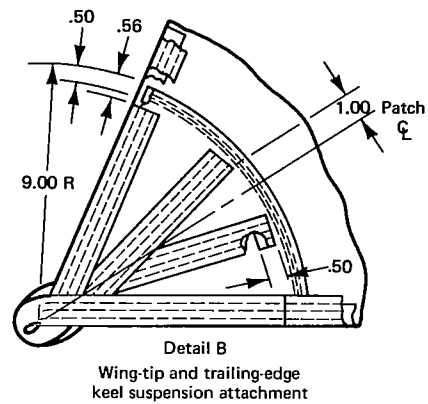
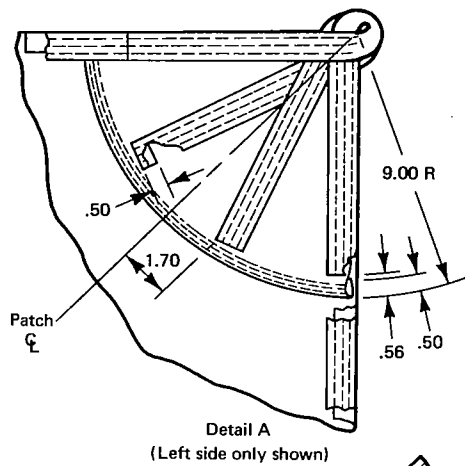
(c) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q = 1$ psf.

Figure 6.- Concluded.



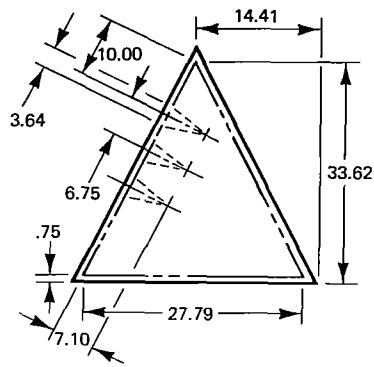
(a) Pattern details.

Figure 7.- 22.7-ft dual keel parawing with lateral and longitudinal reinforcing tapes.

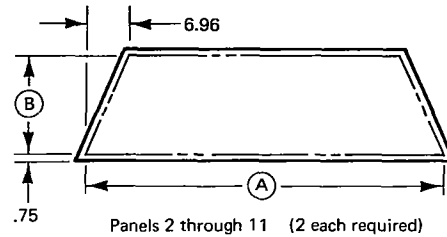


(a) Pattern details - Continued.

Figure 7.- Continued.

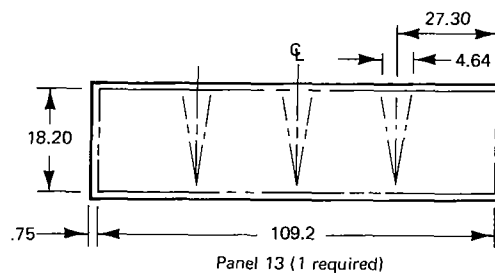
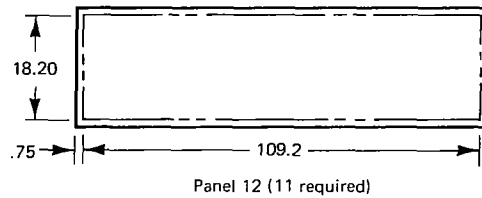
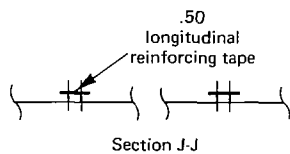
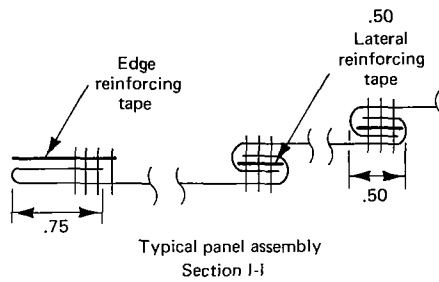
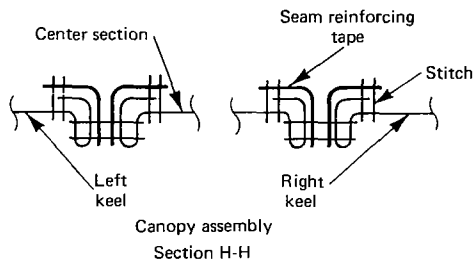


Panel 1 (2 required)
Detail E



Table

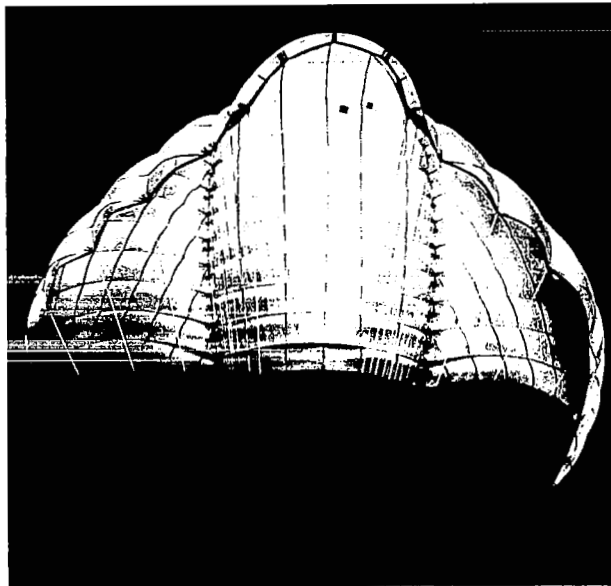
Panel	Dimensions	
	A	B
2	41.72	16.81 ↓
3	55.65	
4	69.58	
5	83.51	
6	97.44	
7	111.36	
8	125.29	
9	139.22	
10	153.15	
11	167.08	



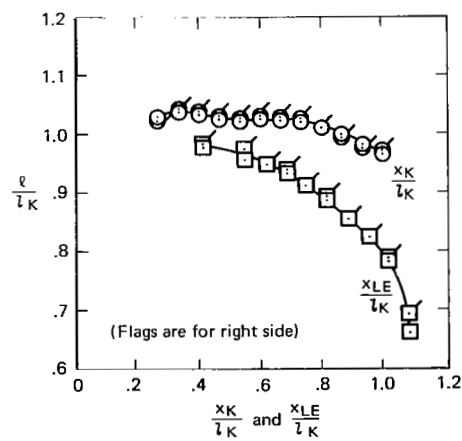
(Note: All dimensions in inches)

(a) Pattern details - Concluded.

Figure 7.- Continued.



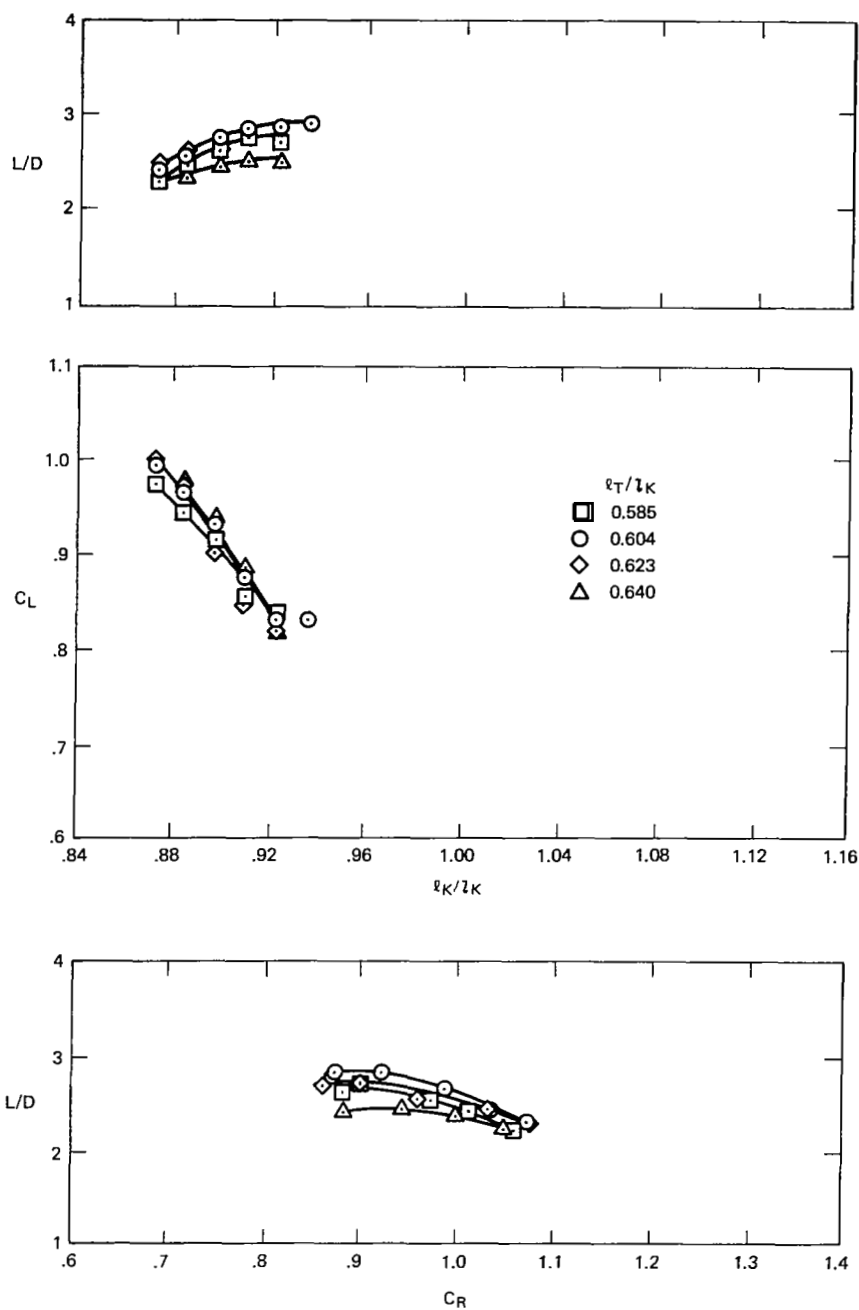
(b)



(c)

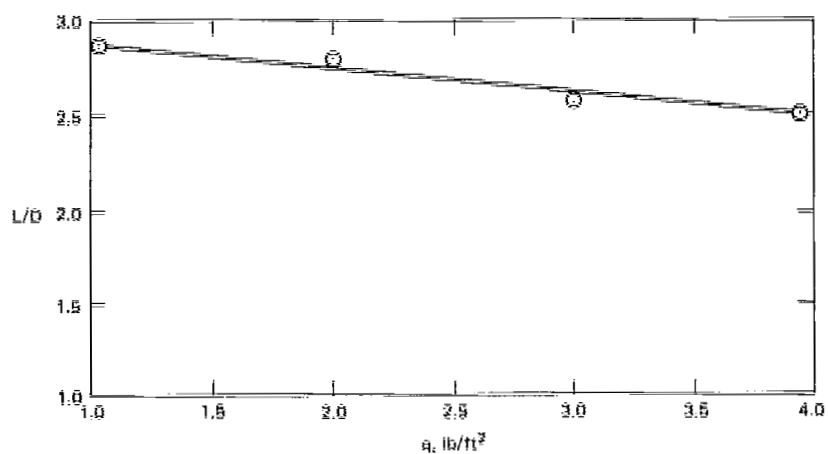
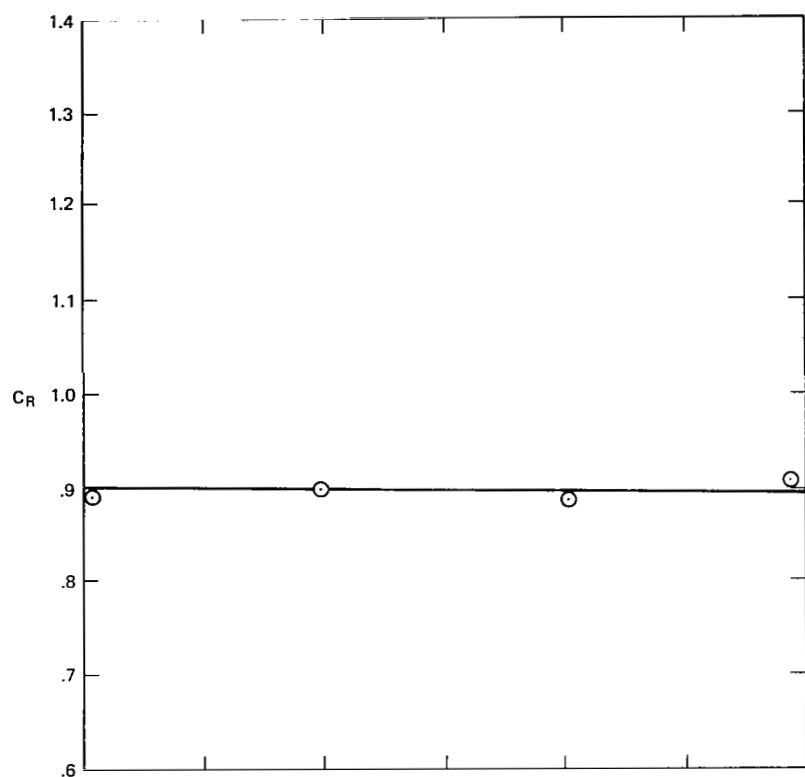
- (b) Photograph of parawing in wind tunnel.
 (c) Suspension line lengths as functions of canopy attachment locations.

Figure 7.- Continued.



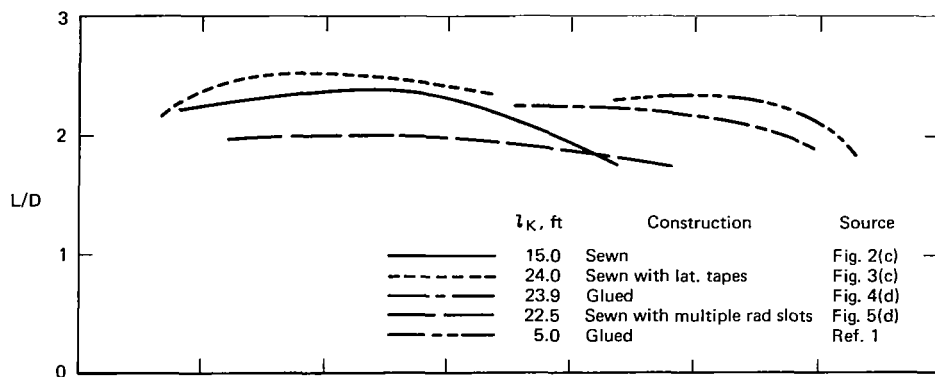
(d) Aerodynamic characteristics for several keel trailing-edge and wing-tip line lengths; $q = 1$ psf.

Figure 7.- Continued.

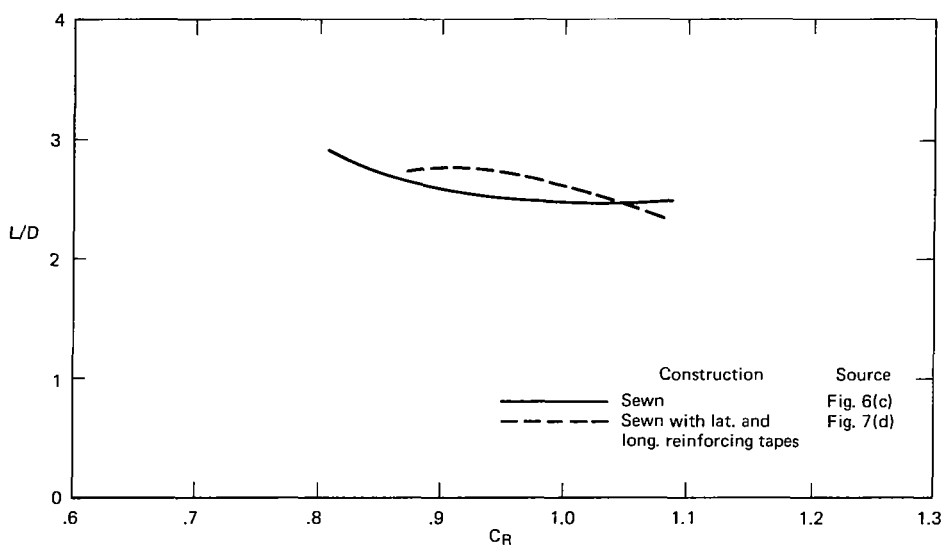


(e) Resultant force coefficient and lift-drag ratio as functions of free-stream dynamic pressure for $l_T/l_K = 0.623$ and $l_K/l_K = 0.910$.

Figure 7.- Concluded.



(a) Single keel parawings.



(b) Dual keel parawings with $l_K = 22.7$ ft ($l_T/l_K = 0.62$).

Figure 8.- Summary of results.